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Copyright Statement

COCTA

COORDINATED CAPACITY ORDERING AND TRAJECTORY PRICING FOR BETTER-PERFORMING ATM

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

Abstract

In this deliverable, the COCTA consortium outlines the research carried out, summarises the main results from a large-scale case study, and highlights research contributions.

The deliverable starts with a COCTA team view on major challenges in the current Air Traffic Management system, proposing a novel institutional setting and operational concept to overcome them. We outline the project's main idea of coordinated capacity and demand management: the Network Manager jointly asks for en-route capacity from Air Navigation Service Providers and defines differentiated trajectory products, selling them to Aircraft Operators at differentiated prices. Although the COCTA process of capacity and demand management spans from several years in advance until the day of operations, the primary focus of this research is on strategic (several months in advance) and pre-tactical stage (up to one day before the day of operations).

Results from a large-scale case study on a European level (Central and Western European airspace, with more than 11,000 flights) indicate that the COCTA concept improves overall cost-efficiency, when compared to a baseline (which resembles the current system to the extent possible). Results also indicate that the COCTA concept offers a possibility to (cost) efficiently serve the same level of traffic with less resources than in the present system.

We conclude that the COCTA concept shows promising preliminary results and outline potential future research and innovation activities.

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1 Executive Summary

COCTA is an exploratory research project funded by the SESAR Joint Undertaking within the European Union's Horizon 2020 research and innovation programme under grant agreement No 699326.The project is led by University of Belgrade – Faculty of Transport and Traffic Engineering (UB-FTTE), project coordinator, with University of Warwick (UW) and Worms University of Applied Sciences (HW) as partners. COCTA is a fundamental research project with a goal to achieve maturity level TRL 1[1] by the end of the project, setting a foundation for future research and defining next research steps.

COCTA addresses the Research Topic ER-01-2015: Economics and Legal Change in ATM with the aim to explore a novel approach to capacity and demand management, employing economic instruments on both sides of inequality, as opposed to the current, predominantly administrative measures. Initially, COCTA targeted a year 2050 horizon with most of the SESAR operational concepts implemented, especially at the network operations level. Nevertheless, some aspects of the COCTA concept can be implemented within a shorter time horizon, as suggested by the Advisory Board (AB) members.

In the COCTA project, we develop a novel capacity and demand management concept aiming to timely harmonize air traffic demand and airspace capacity by means of orchestrated application of economic instruments – incentives and variable-pricing mechanisms. The objective of COCTA is to propose and evaluate a redesigned ATM environment in which the Network Manager (NM) co-ordinately asks for airspace capacity from Air Navigation Service Providers (ANSPs) at strategic and pre-tactical levels and offers routes through trajectory-based pricing to Aircraft Operators (AOs), to optimize the overall network performance.

In the proposed setting, the NM asks for/orders airspace capacities from ANSPS, in line with expected demand distribution in the network. This capacity ordering process has several stages: long-term (several years), strategic (several months) and pre-tactical (several days and up to day before operations). On the demand side, COCTA introduces an airport-pair based charging principle to incentivise more predictable route choices; the base charge for a flight between two airports only depends on the MTOW of an aircraft. Building upon capacity ordered, the NM defines different trajectory products and offer them at differentiated charges, compared to the base charge, to AOs, thus employing economic (incentives) measures to manage demand. Therefore, the NM employs trajectory charging to (re)distribute demand in the network, aiming at establishing an appropriate balance between cost-efficiency, delays, environmental impacts and equity, without negatively affecting safety. Once AOs choose their trajectory products, the NM decides on the final trajectories (subject to negotiations with AOs), within pre-agreed margins for temporal or lateral deviation from the preferred trajectory.

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[1] Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest. When a technology is at TRL 1, scientific research is beginning and those results are being translated into future research and development.

We develop a mathematical model for the proposed concept and evaluate it using a large-scale case study: more than 11,000 flights and 50,000 trajectory options, in the airspace with 8 ANSPs in Central and Western Europe with more than 170 potential airspace configurations.

The results show the following:

- COCTA improves total cost-efficiency, that is, cost of capacity provision and displacement cost, compared to a Baseline, which replicates the current system to the extent possible.
- Cost of capacity is (pre)determined longer in advance (several months/years), i.e. at strategic and long(er)-term basis, and the COCTA concept demonstrates how to maximize the utilization of capacity ordered using trajectory products differentiation and pricing incentives (demand management).
- With novel approach to demand management, the NM is able to steer AO trajectory choices to maintain a system optimum capacity-demand balance and network performance indicators from strategic stage.
- Compared to the Baseline scenario, COCTA is able to substantially reduce delay and especially longer delays (45+ minutes) as indicators of equity.
- This major delay savings comes at the expense of somewhat higher CO_2 emissions of a few additional kilograms per flight on average. It should be noted, however, that this additional CO_2 emission is compared to shortest route, since the COCTA airport-pair charging does not send any incentive to fly longer routes (absent winds). One should note, however, that different policy goals, which explicitly include targeted level of emissions, would lead to different decisions taken by the NM, e.g. to order more capacity or to increase delays, to avoid re-routings and emissions.

The primary impact of implementation of the COCTA concept is improving total cost-efficiency, i.e. total cost of capacity provision and costs of delays and re-routings. These costs are borne by AOs, and ultimately, by users of air transport (passengers). Based on the consultation with stakeholders, the proposed concept should not require major changes in the way they conduct their business.

Another impact of implementation of the COCTA concept of operations is improving capacity KPA. COCTA mechanism allows not just more traffic to be handled with the same level of capacity, but also to reduce delays (especially long delays) imposed to AOs.

The COCTA concept also has an impact on the environment. Namely, proposed airport-pair charging principle does not send incentives to AOs to choose longer routes and burn more fuel, to save on the airspace charges (absent wind). Moreover, the NM does not have an incentive to offer longer routes to AOs, unless in cases where it is more cost-efficient. The scope of re-routings can elegantly be adjusted based on the overall policy goals set by the policy maker, which will affect the NM's decisions regarding both capacity ordered and trajectory products offered to AOs.

In the five-month project extension, we updated the COCTA concept and introduced a new approach to solve the mathematical model used to evaluate the concept. In the updated concept, we introduce an additional trajectory product, which grants flexibility to AOs to choose their final trajectory and "prioritize" their flights (e.g. to avoid high delays, similar to the User Driven Prioritization Process). A new approach to solve the model is based on the problem decomposition (capacity and demand decisions), combining machine learning and linear programming. We evaluated the new concept using a medium-scale case study with more than 1,000 flights in a two-hour window crossing the same airspace as in the large-scale case study (note that this demand is quite challenging for the capacity available in some parts of the network). The results, unsurprisingly, suggest that allowing such level of flexibility for some flights could have a potential negative impact on the overall cost-efficiency. This stands if the capacity (sector-opening scheme) is already fixed and cannot be further adjusted and fine-tuned to the demand. More research should be done to make a firm conclusion regarding the potential benefits of introducing the premium trajectory in the COCTA concept.

1.1 Preview of COCTA achievements

The main achievements of the COCTA project have been (in chronological order):

- Review of the current relevant literature, both academic and practical, on Air Traffic Flow Management (ATFM), economic principles of regulation and from relevant and/or similar markets (electricity and telecommunication, brokerage and retailing) and operational research (OR) work that we can exploit and build on in the design of solution methodologies for ATFM problems [1].

- A journal paper addressing the ATFM problem, as observed from AOs', the NM's and ANSPs' perspectives in the current ATM value-chain, with some aspects relevant for COCTA research [2].

- Initial COCTA concept [3], model and mathematical formulation, tested using an academic example of small size [4].

- Redesigned ATM value-chain, with a new role for the NM to co-ordinately ask for en-route capacity from ANSPs (capacity management) and define and offer trajectory products to AOs (demand management). We also define a process (timeline) for capacity and demand management [5].

- Initial capacity and demand management actions and products (COCTA mechanism) to be tested using small-scale case study and fine-tuned based upon an analysis of its results [6].

- We present primary data source used for model testing and evaluation, namely Eurocontrol Demand Data Repository (DDR2) service and Eurocontrol Network Strategic Tool (NEST) used for data sourcing. We detail capacity (elementary sectors, collapsed sectors, configurations, etc.) and demand related data (e.g. last filed flight plan routes), as well as the process of generating additional trajectories used in model testing [7].

- Building upon the initial COCTA model, we develop the first version of a mathematical model of coordinated capacity and demand management actions in a redesigned ATM value chain. We use a relatively small example: 150 flights using airspace with five ANSPs within a 2-hour window. We analyse fundamental trade-offs between ordering more capacity (and increasing cost of capacity provision) and applying less demand management actions (delays or re-routings) to lower cost of displacing flights from their preferred routes (displacement cost). [8]

- We define the final COCTA mechanism, including all the capacity and trajectory products, as well as placing them within the COCTA process of capacity and demand management timeline [9].

- The SESAR Innovation Days 2017 COCTA paper describes the NM's decision-making process regarding capacity ordering at strategic stage, which we demonstrate using a small-scale case study [10]

- We analyse the computational challenges of incorporating trajectory pricing decisions and airlines' choice behaviour into the mathematical model. A parallel is drawn from COCTA to the generic revenue management context to come up with a model formulation. We propose a solution approach based on the idea of re-solving a deterministic approximation of the model several times during the booking horizon. The precision and scalability of the approach is tested with examples of increasing size [11].

- Following a successfully organised COCTA workshop for stakeholders in Frankfurt, Germany, on 27th September 2017, we report the most important feedback received. As a part of the workshop report, we also add an additional data report, including large-scale data analysis (evaluating representative days in the European network) [12].

- We test and evaluate the final COCTA model using a large-scale case study: more than 11,000 flights, with more than 50,000 different trajectory options, crossing airspace of Central and Western Europe - 8 ANSPs, 15 ACCs/sector groups and more than 170 possible sector configurations [13]. We model the entire COCTA process (strategic and pre-tactical), including comparison to a baseline scenario, which mimics the current system to the extent possible [14].

- In [15], we incorporate recommendations received from stakeholders, airspace users in particular. Namely, we introduce a new trajectory product which allows airlines to define their preferred trajectories and the flexibility required for each flight, as well as to decide on the final trajectory. We analyse and evaluate the effects on network performance using a medium-scale case study.

The COCTA consortium and the COCTA Advisory Board members are positive that the COCTA concept and model, i.e. research solutions, have achieved the maturity level TRL1 and are ready for moving to the next R&I phase, more precisely Exploratory Science/Applied Oriented Research.

2 Project Overview

2.1 Operational/Technical Context

The current role of the NM in Europe in the process of establishing a balance between air traffic demand and airspace/airport capacity is merely moderation between AOs and capacity providers, since the NM has limited instruments at disposal to actually influence capacity or demand side decisions [16]. The European Commission (EC) also recognizes that the lack of the NM's clear executive powers in practice means that the NM 'tends to decide by consensus, which often results in weak compromises' [17]. The EC however stresses that an optimisation of the network performance necessitates an extended operating scope of actions by the NM [17]. Furthermore, one of the biggest airlines in Europe also shares the view of the EC, stating that the '*NM's role is to manage the system, optimise traffic flow & route design, coordinate ATC system upgrades, enable continuity of service during disruption, reduce delay & inefficiency*' [18].

Although the NM initiates planning several months before the day of operations, most of demand-capacity imbalance situations are still resolved on the day of operations. This is done by means of administrative demand management actions, often resulting in delays, longer routes flown, hence additional fuel consumption and CO_2 emissions, and even flight cancelations. For instance, total en-route Air Traffic Flow Management (ATFM) delay was 8.7 million minutes across more than 10 million flights in Europe in 2016 [19]. The Performance Review Commission (PRC) estimates associated en-route ATFM delay cost at 867 million EUR [19], using the average cost per minute of ATFM delay estimated in [20]. More than 55% of total en-route ATFM delay is attributed to (lack of) capacity and staffing reasons, while approximately half of that delay occurred during the peak summer months June, July and August 2016, as shown in Figure 1 [19].

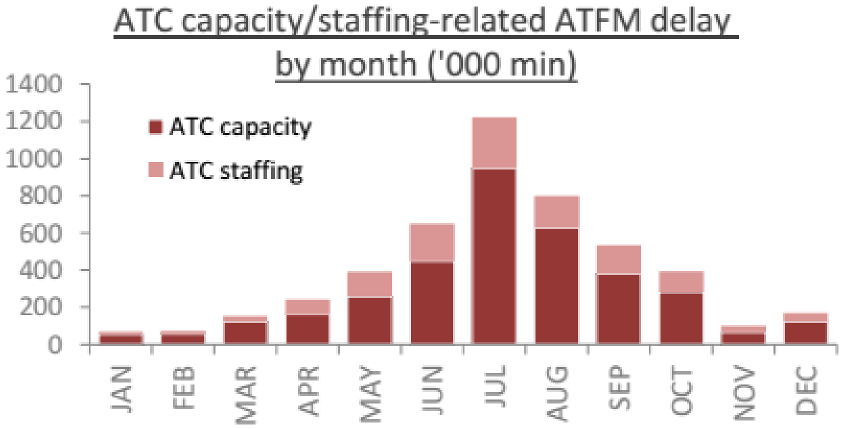
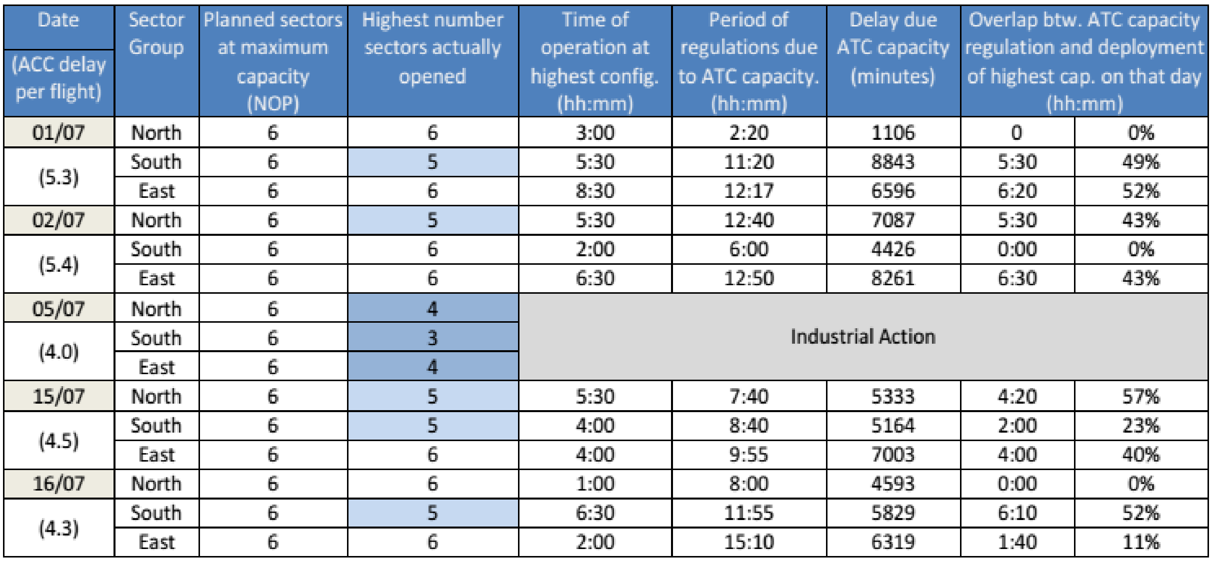


Figure 1. ATC capacity and staffing-related ATM delay [Source: 19]

Even though capacity plans and capacity dimensioning for ANSPs are made based on busy summer traffic patterns [21], the majority of en-route ATFM delays due to lack of capacity occur during summer. Namely, within the framework of the Single European Sky (SES), the NM conducts planning and management of the European ATM Network. Commission Regulation (EU) No 677/2011 details, inter alia, the tasks of the NM and describes the Network Operations Plan (NOP). In the planning phase, the NM shall provide a NOP with a detailed capacity assessment, analysis and requirements for each ANSP, including the following elements: overall network capacity requirements, local capacity requirements, local capacity baselines, local delay targets (more details in COCTA deliverable D2.1 – State of the art report [1]). Moreover, whereas the NM provides required capacity profiles for ANSPs, it does not have a mandate to decide on the actual capacity delivery of ANSPs.

The PRC notes that the capacity requirements are frequently not met by some ANSPs, that is Area Control Centres (ACCs), but also that maximum capacity is not delivered at the time when it is needed. For instance, the PRC shows an example where an ACC was unable or reluctant to open the maximum number of sectors (Table 1, columns 3 and 4), even though the demand levels were high and massive delays were accruing [19]. Secondly, the PRC emphasises that there are significant mismatches between the deployment of maximum capacity and the traffic demand (Table 1, last two columns), evidenced by the necessity to apply regulations for lengthy periods when only a limited number of sectors are opened[2] [19].



Date (ACC delay per flight)	Sector Group	Planned sectors at maximum capacity (NOP)	Highest number sectors actually opened	Time of operation at highest config. (hh:mm)	Period of regulations due to ATC capacity. (hh:mm)	Delay due ATC capacity (minutes)	Overlap btw. ATC capacity regulation and deployment of highest cap. on that day (hh:mm)	
01/07	North	6	6	3:00	2:20	1106	0	0%
(5.3)	South	6	5	5:30	11:20	8843	5:30	49%
	East	6	6	8:30	12:17	6596	6:20	52%
02/07	North	6	5	5:30	12:40	7087	5:30	43%
(5.4)	South	6	6	2:00	6:00	4426	0:00	0%
	East	6	6	6:30	12:50	8261	6:30	43%
05/07	North	6	4	Industrial Action				
(4.0)	South	6	3					
	East	6	4					
15/07	North	6	5	5:30	7:40	5333	4:20	57%
(4.5)	South	6	5	4:00	8:40	5164	2:00	23%
	East	6	6	4:00	9:55	7003	4:00	40%
16/07	North	6	6	1:00	8:00	4593	0:00	0%
(4.3)	South	6	5	6:30	11:55	5829	6:10	52%
	East	6	6	2:00	15:10	6319	1:40	11%

Table 1. Capacity provision issues in the current practice [Source: 19]

Mismatch between capacity provision and traffic demand has several root causes, which originate both at strategic and at pre-tactical levels. One of the underlying causes for capacity and demand mismatch is traffic variability (and volatility). This is inherently linked to traffic (materialisation) uncertainty: while scheduled traffic (~80% of total demand) is largely known several months in advance, non-schedule traffic like business and charter flights are not known with the same level of reliability. If traffic is highly variable and there is limited flexibility to adjust the capacity provision according to actual traffic demand, the result may be poor service quality or an underutilisation of resources [19]. If addressed proactively, traffic variability can be mitigated or resolved to a certain degree by utilising previous experience, roster staffing levels to suit and to make more operational staff available by reducing ancillary tasks performed by ATCOs during the peak period [19]. Figure 2

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[2] The Provisional Council, in recommendations from PRR 2014 and PRR 2015, highlighted the need for capacity to be made available during peak traffic periods rather than regulating demand to meet reduced capacity.

illustrates capacity utilisation of a portion of European airspace based on one week of traffic during summer 2017. It indicates that half of the time, sectors' utilisation is less than 60%, just below average sector load of 62% [22]. There are both spare capacity and shortages, with negative impact on both cost of capacity and delays [22]. While delay costs occur when there is no sufficient capacity, better allocating or reducing spare capacity should also lead to lower costs of capacity provision for airspace users.

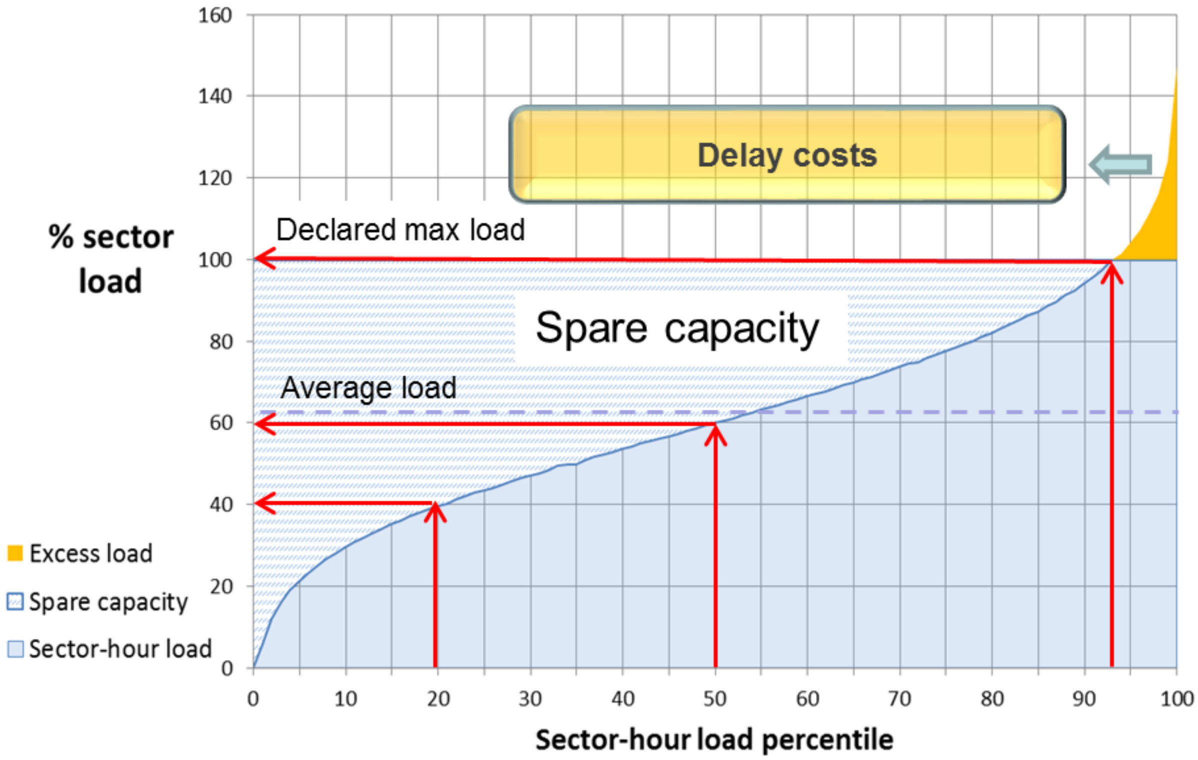

Figure 2. Airspace capacity utilisation [Source:22]

ANSPs have to plan their capacities months and weeks in advance, with only very limited and costly possibilities to adjust those, especially upwards, on a short notice [23]. They have to account for both traffic variability at strategic level when planning sector-opening schemes (SOSc) and rostering, but also to account for traffic (un)predictability at shorter notice. Namely, AOs attach great value to flight planning flexibility and tend to reveal their route choice decisions only hours before the time of departure to benefit from up to date relevant information. Although last moment route-choice cost savings could be at most a few hundred euros per flight ([24], [25], [26]), such behaviour reduces predictability for ANSPs and the NM. Hence, a consequence on a network level could be lower utilization of available capacities and/or higher costs imposed on other AOs, as well as a likely deterioration of the network performance as a whole [27]. The fact that the demand is inherently heterogeneous and that some AOs in some cases choose a route which seems to be inefficient (distance- or/and charges-wise) [26], [28], adds to the complexity of predicting the AOs' route choice, hence the optimal capacity provision (to a certain extent).

In addition, the current route charging system in Europe does not provide any incentives to reduce the mismatch between capacity provision and demand. Charges for air navigation services are set according to an average cost approach, with different rates in neighbouring areas. This does not provide incentives to adjust capacity shortages and may lead to environmentally inefficient outcomes if an AO chooses a longer flightpath due to lower charges. Moreover, for ANSPs the regulatory framework has changed significantly over the last years. Traditionally, ANSPs were subject to a pure cost-based regulation. The current regulatory framework introduced elements of incentive regulation, aiming at a reduction, or at least limitation, of the overall charging level. However, ANSPs still apply a rather simple charging structure without differentiations other than the aircraft Maximum Take-Off Weight (MTOW).

The trade-off between the predictability for ANSPs and the flexibility for AOs results in substantial and costly capacity buffers built into ANSP planning decisions. For instance, one ANSP estimated that approximately 5-10% of its capacity is actually 'reserved' to take care of all predictability and non-adherence issues arising in pre-tactical and tactical stages. Potential cost savings arising from a more predictable system are estimated to 45 million EUR per annum for that provider [29]. Similarly, costly buffer times are built into AOs schedules. For example, for AOs in the US approximately 6 billion USD was associated with schedule buffers [30], embedded to compensate for (a portion of) anticipated delays from all causes, while maintaining the on-time performance of flights and the operational reliability of schedules [31].

We recognize the issues of traffic variability and predictability and the need for capacity provision flexibility as some of the major challenges in today's ATM value-chain and propose a potential solution within the "Coordinated capacity ordering and trajectory pricing for better-performing ATM", COCTA project (acronym).

2.2 Project Scope and Objectives

Within COCTA, we develop a concept to timely harmonize air traffic demand and airspace capacity by means of orchestrated application of economic instruments – incentives and variable-pricing mechanisms – on both demand and capacity side. The objective of COCTA is to propose and evaluate a redesigned ATM environment in which the NM coordinately asks for airspace capacity from ANSPs at strategic and pre-tactical levels and offers routes through trajectory-based pricing to AOs, in such a manner to optimize the overall network performance.

We envisage a new role for the NM, empowering it to coordinately take capacity and demand management decisions, by means of economic instruments, supported by a redesigned ATM value-chain. The NM also has the responsibility for optimising network performance, as defined by the policy maker. Policy objectives might include acceptable ranges of network performance indicators, including areas of cost-efficiency, capacity, environment, equity, etc.

The key proposed change concerns the relationship between the NM and the ANSPs[3]. In the proposed setting, the NM asks for airspace capacities in line with expected network demand, employing a network-centred, demand driven approach, as opposed to the current piecemeal supply driven practice, which is tailored against local/ANSP traffic peaks [21]. The capacity ordering process spans from long-term (several years) through strategic (several months) to pre-tactical phases (several days before day of operations), addressing traffic variability in each step with updated

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[3] Within the general COCTA context, airports are considered to be fairly passive capacity providers. As such they are not explicitly included into the modelling.

demand information. Consequently, better utilisation of en-route capacity is expected, with associated beneficial cost implications, since ANSPs can plan their resources in timely manner.

Planning processes have already been identified as the most significant drivers of an air traffic control centre's cost-efficiency [32]. As those processes determine staffing, which is the main resource of a centre, as well as airspace sector-opening sequences, an overestimation of traffic demand in the planning process can result in a low cost-efficiency performance of a centre. Therefore, designing a new ATM value-chain which also increases the predictability in terms of AOs' route choices should increase predictability for ANSPs in terms of staffing (shift planning etc.) on the day, e.g. whether maximum configuration is to be applied [32].

Therefore, on the demand side, COCTA introduces an airport-pair based charging principle to incentivise more predictable route choices. Within the COCTA concept, the base charge for a flight between two airports, i.e. the charge without applying additional demand management incentives, only depends on the MTOW of an aircraft. Unlike the current charging scheme, airlines do not have an incentive to deviate from the shortest route between two airports to reduce en-route navigation charges. The application of this airport-pair-based charge should reduce CO_2 emissions and make AOs' route choice more predictable.

Building upon capacity ordered and applying the airport-pair charging principle, the NM defines different trajectory products and offer them at differentiated charges to AOs, thus employing economic (incentives) measures to manage demand. Mindful of AOs business needs and preferences, the NM defines trajectory products in such manner to govern their trajectory (route) choice to establish a demand-capacity balance. Practically, the NM employs trajectory charging to (re)distribute demand in the network, aiming at establishing an appropriate balance between cost-efficiency, delays, environmental impacts and equity, without negatively affecting safety.

The hypothesis is that the NM will ask for and use (coordinate) airspace capacity in a more efficient manner compared to the present situation, recognising that airspace capacity is lumpy and not likely to be available for ordering in tiny increments, which would be ideal in terms of minimisation of unused capacities.

To summarize the main COCTA objectives:

- propose a re-designed ATM value-chain, with new roles for the stakeholders, to introduce a novel approach to coordinated capacity and demand management;
- define a capacity and demand management process for strategic and pre-tactical stage, including capacity and demand related products and transactions between stakeholders;
- develop a conceptual model, with corresponding mathematical mode,l which captures the most important aspect of the concept;
- assess if the proposed concept is more cost-efficient than the current system and evaluate the impact on the other network performance indicators;

2.3 Work Performed

The COCTA research breakdown per work-packages, their relations and steps (flow) are summarized in Figure 3, as well as associated deliverables which represent the outcome of each step (as indicated in the upper right corner of each text box). For the sake of easier understanding, we merge data management with modelling work-package, although they are separate work-packages.

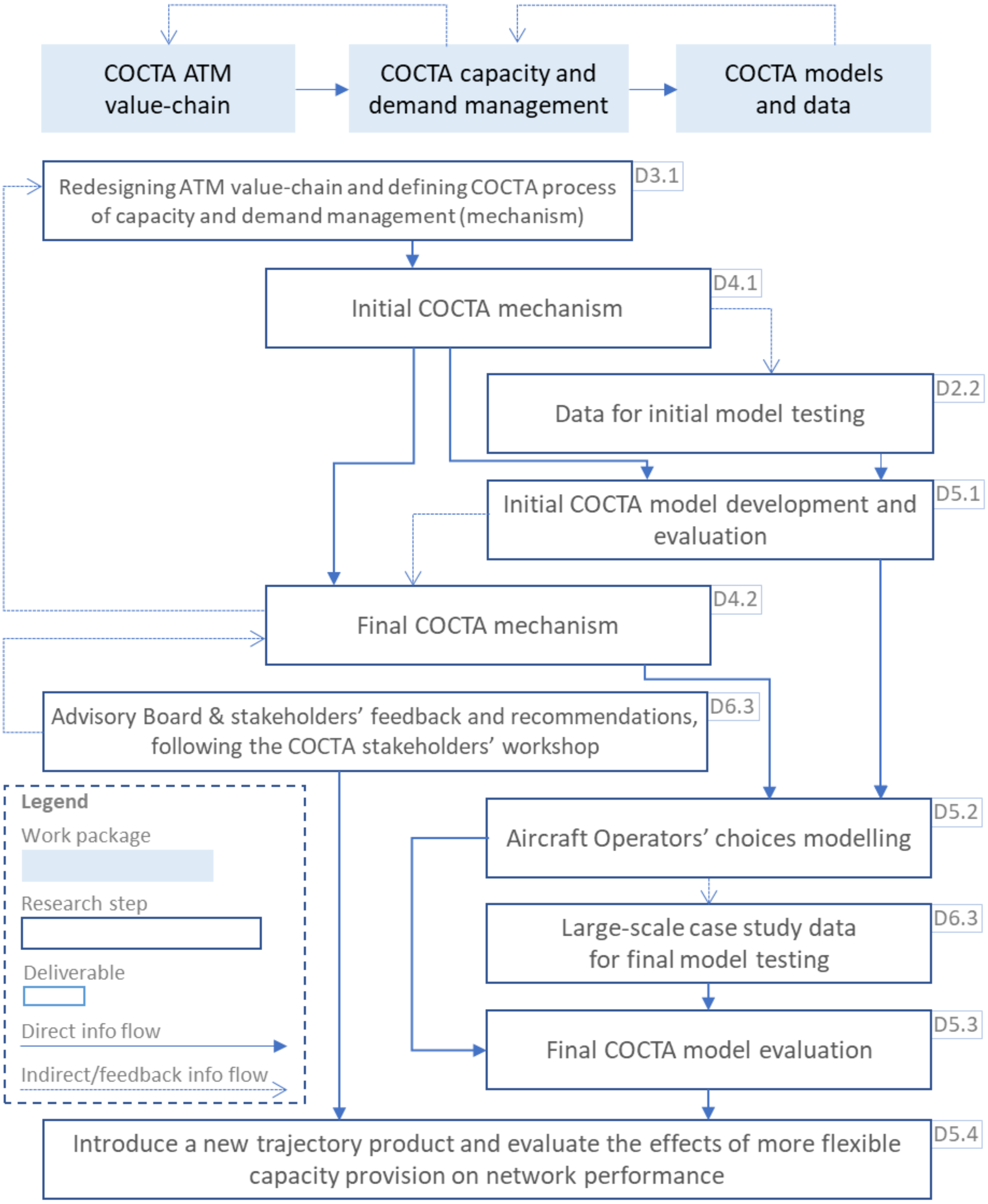

Figure 3. COCTA research steps and associated deliverables

2.3.1 COCTA ATM value-chain

The re-design of the ATM value chain [5] is necessary to make the COCTA capacity and demand management process possible and effective. We hereby offer a brief high-level reflection on each of the key relevant parties, stressing the institutional relationships between them:

- **The Network Manager** aims at optimising the performance of the network by smartly ordering (asking for) airspace capacities and packing them into trajectory products to be offered to AOs.
- **Aircraft Operators**. Unlike most of previous efforts in the field, COCTA assumes heterogeneous demand, that is, it explicitly takes into account that different AOs, at least on a market segment level, may have different objectives and capabilities as far as route choice rationales and flight planning practices are concerned.
- **Air Navigation Service Providers** are generally assumed to remain independent in capacity provision, interacting with the NM. The NM asks ANSPs to provide required capacity levels in agreed timeframe and we consider different options for capacity adjustments, i.e. adapting capacity to demand. Whereas in the short term ANSPs have only limited possibilities to influence the costs of capacity provision, incentives for efficient capacity investments are of importance in the long run.
- **Airports**. Within the general COCTA context, airports are assumed to be passive capacity providers. As such they will not be explicitly included into the modelling.

In the redesigned ATM value chain, the NM has contractual relationships with ANSPs and AOs. On the capacity side, the NM asks for en-route airspace capacity from ANSPs at strategic level, with an option to adjust initial orders within the capacity management process horizon. This horizon spans from several years in advance until the day of operations, involving different capacity products for each stage. Capacity ordering involves negotiation between the NM and ANSPs and a mutual agreement between the stakeholders how much capacity should be provided and delivered for each stage.

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. COCTA introduces an airport-pair based charging principle to incentivise more predictable route choices. Within the COCTA concept, the base charge for a flight between two airports, i.e. the charge without applying additional demand management incentives, only depends on the MTOW of an aircraft. Unlike the current charging scheme, airlines do not have an incentive to deviate from the shortest route between two airports to reduce en-route navigation charges. The application of this airport-pair-based charge should reduce CO_2 emissions and make AOs' route choice more predictable.

The NM also has the responsibility for delivering required network performance, as defined by policy makers. Policy objectives might include acceptable ranges of network performance indicators (including areas of cost-efficiency, capacity, environment, equity, etc.).

An overview of the institutional settings and relationships is given in Figure 4. Details are further elaborated in the following sub-section.

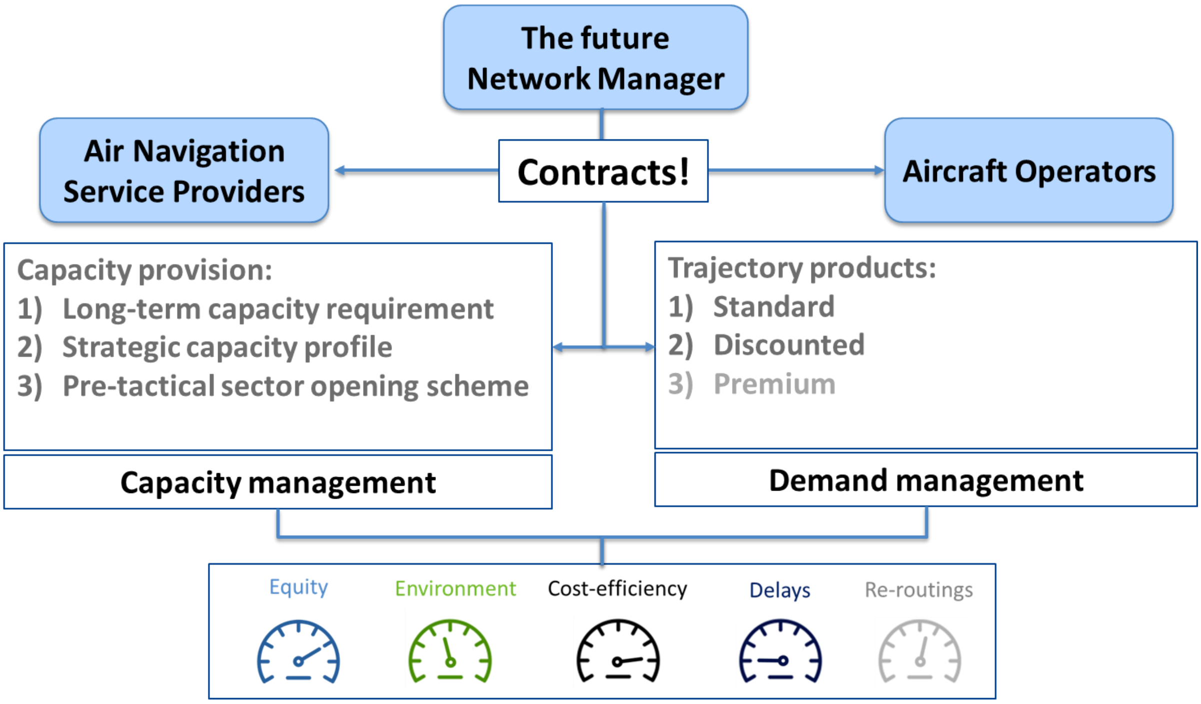

Figure 4. Relationship between stakeholders in the redesigned ATM value-chain

2.3.2 COCTA capacity and demand management process and products (COCTA mechanism)

Building upon the redesigned ATM value-chain described in [5], we further develop the COCTA capacity and demand management process and products: initially in [6], with updates in [9].

The COCTA mechanism represents a joint capacity and demand management process, including products and actions to optimise network performance. Within the COCTA framework, the mechanism is primarily designed for strategic (six months and up to a year in advance) and pre-tactical stages (seven days in advance), while the tactical stage is considered to a certain extent only. In addition, we also discuss long-term (five years) capacity planning and ordering and in this section, we provide a brief overview of the process as a whole.

The NM carries out capacity management at the network level. Due to relatively long lead times related to the capacity planning and provision process [32], the COCTA network capacity planning and management process spans over a five-year horizon. Similar to the current practice, we assume that the NM and ANSPs agree on long-term capacity requirements which need to be delivered on an annual level over the long term (five years), with the difference that this agreement is based on a contract in the COCTA concept. In the long term, the NM, for instance, could expect high level of traffic variability in the network, both in terms of traffic levels overall and spatio-temporal distribution. Therefore, to evaluate how much capacity (profile) is needed for an anticipated demand profile, the NM can use the COCTA mathematical model and run it multiple times with different traffic materialisations in the network (based on long-term forecasts). The output from this analysis is a capacity profile, in the network (per ACC) required to serve anticipated traffic levels in a cost-efficient manner. This capacity requirement is based on long term traffic forecasts and serves as a foundation for ANSP's capacity related decisions (e.g. staff training and technical equipment).

When AOs publish their schedules, around six months in advance of a schedule season, the NM has more precise information on O&D pairs and respective times of operations. Based on information of scheduled traffic and accounting for a portion of non-scheduled demand - which is associated with a higher level of uncertainty in terms of O&D pairs, times of operations and overall traffic levels - the NM defines capacity orders within the capacity profile sketched above. Therefore, about six months in advance, the NM refines and makes a more precise capacity order from the ANSPs, aligned with the long-term order. This capacity ordering decision is based on the evaluation of results of the COCTA mathematical model testing at the strategic level (details on model testing provided in the next section). The NM asks for capacity from ANSPs, which is measured using sector-hours. Depending on assumed flexibility of capacity provision in terms of ANSPs' staffing practices, i.e. how much in advance ATCOs rostering is defined, the NM can define its initial order as a sector-opening scheme (less flexible) or as total sector-hours to be delivered on that day, including maximum number of sectors to be opened and duration of the maximum configuration (more flexible). The capacity management process continues after this decision, with options to slightly adjust the initial capacity order, in line with flight intentions information received/updated subsequently, again, depending on the assumed flexibility of capacity provision. In any case, at the pre-tactical level, the NM and the ANSPs should agree on a sector-opening scheme to be delivered on a day of operations.

In the redesigned ATM value-chain, we also foresee a novel approach to demand management, which becomes trajectory (product) management. The trajectory management process (lifecycle) starts at strategic level and spans until a flight has been executed. Again, in the current COCTA concept, we focus on strategic and pre-tactical phases.

At strategic level, the NM demand management is used primarily to establish a cost-efficient balance between demand and capacity. Namely, the NM evaluates if it is more cost-efficient to delay or re-route flights in certain parts of the network, instead of asking ANSPs to provide more capacity. Moreover, in some parts of the network and during certain periods (peak hours), demand profile might be such that even maximum (structural) capacity might not be sufficient to accommodate anticipated demand without delays (or re-routings). Therefore, using available information on flight intentions (scheduled carriers) and anticipated/forecasted level and spatio-temporal distribution of non-scheduled flights (e.g. charters and business aviation), the NM evaluates what is the scope of demand management actions, combined with capacity ordering (management), that minimises total cost to AOs. As a result from this analysis, the NM has information on capacity needed per ANSP and the scope of delays and re-routings of flights/flows in the network, which establishes a cost-efficient balance between anticipated demand and capacity ordered.

After the initial capacity order, the NM starts defining trajectory products to incentivise AOs' route/trajectory choice to maintain, to the extent possible, the strategically established balance between demand and capacity, which minimises total cost to AOs. Therefore, the NM steers demand by defining and offering different trajectory products, at differentiated prices, to AOs. These products are for the sake of simplicity labelled Standard Trajectory (ST), Discounted Trajectory (DT)[4]

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[4] Note that Standard Trajectory is referred to as Purchased Specific Trajectory (PST) and Discounted Trajectory as Flexibly Assigned Trajectory (FAT) in most of the COCTA deliverables and publications. Trajectory products are renamed in the deliverable D5.4 - Effects of increased flexibility for airspace users on network performance, with the introduction of the Premium Trajectory.

and Premium Trajectory (PT). For instance, ST is associated to the shortest route between two airports, including relatively narrow and pre-agreed spatio-temporal trajectory margins, necessary for trajectory fine tuning at a later stage (e.g. shortly before take-off). This product comes at a base charge and is tailored for flights/flows which are not suitable “candidates” for demand management actions. On the other hand, by choosing a DT, an AO gets a lower charge compared to the ST product, but delegates the decision to the NM to delay or re-route its flight within pre-agreed margins (usually wider than those for ST). With PT, AOs have an option for last minute trajectory changes, either in space or time, within agreed margins; this option comes at a higher charge compared to the ST.

To sum up, the NM offers a range of trajectory products, at differentiated charges, to incentivise AOs’ trajectory/route choices to the extent possible, to achieve required network performance.

2.3.3 COCTA modelling, model testing and data used

2.3.3.1 COCTA model

We define a mathematical model for capacity ordering and trajectory pricing and demonstrate the NM’s joint decision-making using a large-scale example based on real data. The COCTA model evolved from the initial model formulation [8] and airlines’ (trajectory) choice model [11] to the final model described in [14].

Primary focus of the COCTA model is to analyse principal trade-offs between capacity and demand management actions to improve overall cost-efficiency:

- Asking for (more) capacity, and thereby increasing the cost of capacity provision, to reduce costs of delaying or re-routing vs
- Delaying or re-routing flights in order not to increase the costs of capacity provision.

Hereby, we provide a high level overview of the COCTA model, while detailed description, mathematical formulation and solution approach can be found in [14].

We assume that the NM’s primary aim is to ask for capacities across the network to maximize cost-efficiency, i.e. to minimize the sum of capacity provision and displacement costs (objective). In addition, we also examine trade-offs between different performance indicators such as capacity, environment and equity.

The model takes into account limited en-route airspace capacity, that is, declared capacity of Air Traffic Control (ATC) sectors within an ACC. By capacity, we refer to number of aircraft that can enter a sector, controlled by a pair of ATCOs, per hour (so called ‘entry counts’). The model also considers how these sectors can be combined into different airspace sector configurations. The more sectors are open in time, the more capacity is (usually) provided and the cost of capacity provision is higher.

On the demand side, there is a set of alternative trajectories for each flight, including preferred one (shortest) and trajectories subject to one demand management measure (delay or re-routing). If a flight is assigned to the shortest route there is no additional cost for an AO. Delaying or re-routing that flight incurs additional cost [20], which we refer to as displacement cost (since the flight is *displaced* from its preferred trajectory either in space or in time).

Basically, the model decides whether to provide more capacity in an airspace, thereby increasing the cost of capacity and decreasing displacement cost, or to displace more flights and increase displacement cost to save it on the capacity side (see Figure 5).

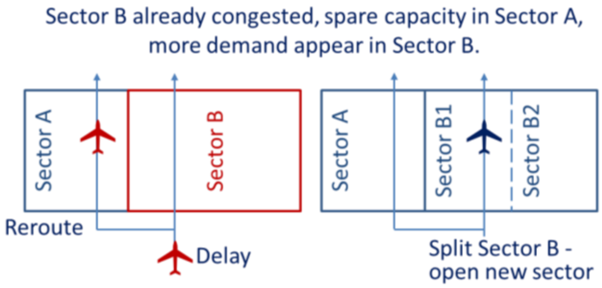

Figure 5. Trade-offs between (the scope of) capacity and demand management measures

2.3.3.2 COCTA model testing

Depending on the timeframe, i.e. long-term, strategic or pre-tactical stage, the model parameters and model testing differ. As already discussed, we carry out detailed model testing for the strategic and the pre-tactical levels.

2.3.3.2.1 Strategic capacity ordering (up to a year in advance)

To demonstrate a more precise capacity order at strategic stage, that is, sector-opening scheme, we choose one representative day in the schedule season. In practice, the NM can test several representative days, associated with distinct traffic levels and traffic patterns; due to a very demanding computation (times) we demonstrate the NM's decision making using one of them. Namely, the NM chooses a narrower range of flights (lower traffic variability), expected to materialise on that day. The NM now has information on scheduled flights (departure and arrival airports, times, aircraft type) and expects all scheduled flights to materialize on that day. However, there is still a portion of non-scheduled demand not known with the same level of reliability as scheduled flights, so we consider them as 'uncertain', introducing some traffic variability (lower than in previous case).

We test the COCTA model with different non-scheduled traffic materialisations in the network and obtain a solution for each iteration: optimal traffic assignment, sector-opening scheme and associated network performance. Based on many iterations and network performance achieved in individual iterations, we define different scenarios by grouping (clustering) similar results. We refer to this step as Scenario Identification (SI) step, which as an output has different capacity ordering (SOSc) policies, associated with distinct network performance levels.

Then the NM evaluates capacity ordering decisions, that is, different SOSc ordered and associated network performance under different traffic scenarios (*what if*). This is the Scenario Testing (ST) step in which the NM tests the performance (including robustness) of each of the identified scenarios in the previous step. In this step, a number of non-scheduled flights is sampled and the COCTA model is solved, now with specific SOSc defined for each ACC. Finally, the NM can compare results (network performance) for the pre-defined set of SOSc and decide on the final capacity budget for each ANSP/ACC. This step concludes the model testing at the strategic level. Output (SOSc) of one of the defined scenarios yielding the desired/acceptable level of the network performance will be selected to constitute an input for the pre-tactical model testing.

For the sake of comparison at this level of analysis, we define a Baseline scenario which should mimic, to the extent possible, the current practice of capacity planning. To facilitate fair comparison, for the Baseline we use the same COCTA model, but with different assumptions, which are in line with the current practice. Namely, for the Baseline scenario, we assume that the NM also tries to find the most cost-efficient solution. We thus use the same COCTA model, with the difference that the NM considers delays as a sole demand management measure, without considering re-routings at this stage [21].

2.3.3.2.2 Pre-tactical trajectory management (up to the day before operations)

Timeframe-wise, the next level for model testing starts after the strategic level, spans across the trajectory booking horizon and ends with pre-tactical trajectory assignment. At this level, the NM has to define trajectory product margins and prices and offer them to AOs to ensure recovery of capacity costs. Like in the current practice, in the COCTA concept the cost recovery should be ensured on an annual (or semi-annual) level. 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). At pre-tactical level, we compare three different pre-tactical scenarios: COCTA, Baseline and NEST (only for the maximum number of flights anticipated in the network).

COCTA scenario. Regarding the network performance, the NM has already decided on SOSc per ANSP/ACC, based on simulation and assessment of the network performance, using different traffic samples, as sketched above. While the NM assigns flights to “optimal” trajectories in simulation from its perspective, in the booking horizon AOs choose and decide among different available trajectory products. Therefore, 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. Note that, based on the assumed level of flexibility, SOSc can be adjusted/modified to meet demand. To effectively improve and/or maintain the network performance, the NM needs to infer, at least, expected behaviour of different AOs when choosing trajectory products. As a reminder, the NM uses DT products to be able 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 the available capacities. The idea is to test how the NM can manage the demand, once the decision on SOSc had been made and what would network performance be under different traffic levels expected for that day of operations. This may call for computation of one further indicator, and that would be some indicative cost of capacity provision per flight (or per traffic unit). Since we asked for a SOSc and the volume of materialized traffic can vary, the unit cost of capacity provision could go up if less traffic than expected materializes. In other words, not all indicators are improved when we have lower traffic levels in the pre-tactical phase than anticipated.

Baseline scenario. For the Baseline scenario at the pre-tactical level, we assume that some flights might take longer routings, but just up to a certain margin (as elaborated in the results section). Like in the strategic case, we use the same traffic samples across different pre-tactical scenarios. If there is no sufficient capacity, the NM assigns delay to flights, trying to minimise minutes of (ATFM) delay, instead of delay costs (to mimic the current system).

The NEST scenario. We also generate a scenario with the maximum number of flights using the EUROCONTROL NEST tool. Flights are assigned to shortest routes, and based on this spatio-temporal traffic distribution, NEST defines SOSc using the Improved Configuration Optimiser (ICO) algorithm [33]. ICO can generate an opening scheme which minimizes overloads and the number of controller positions whilst maintaining sustainable workload in the activated sectors according to the declared sector/TV capacities, all for a given level of traffic and controller availability [34].

Model testing steps at different levels are summarized in Figure 6.

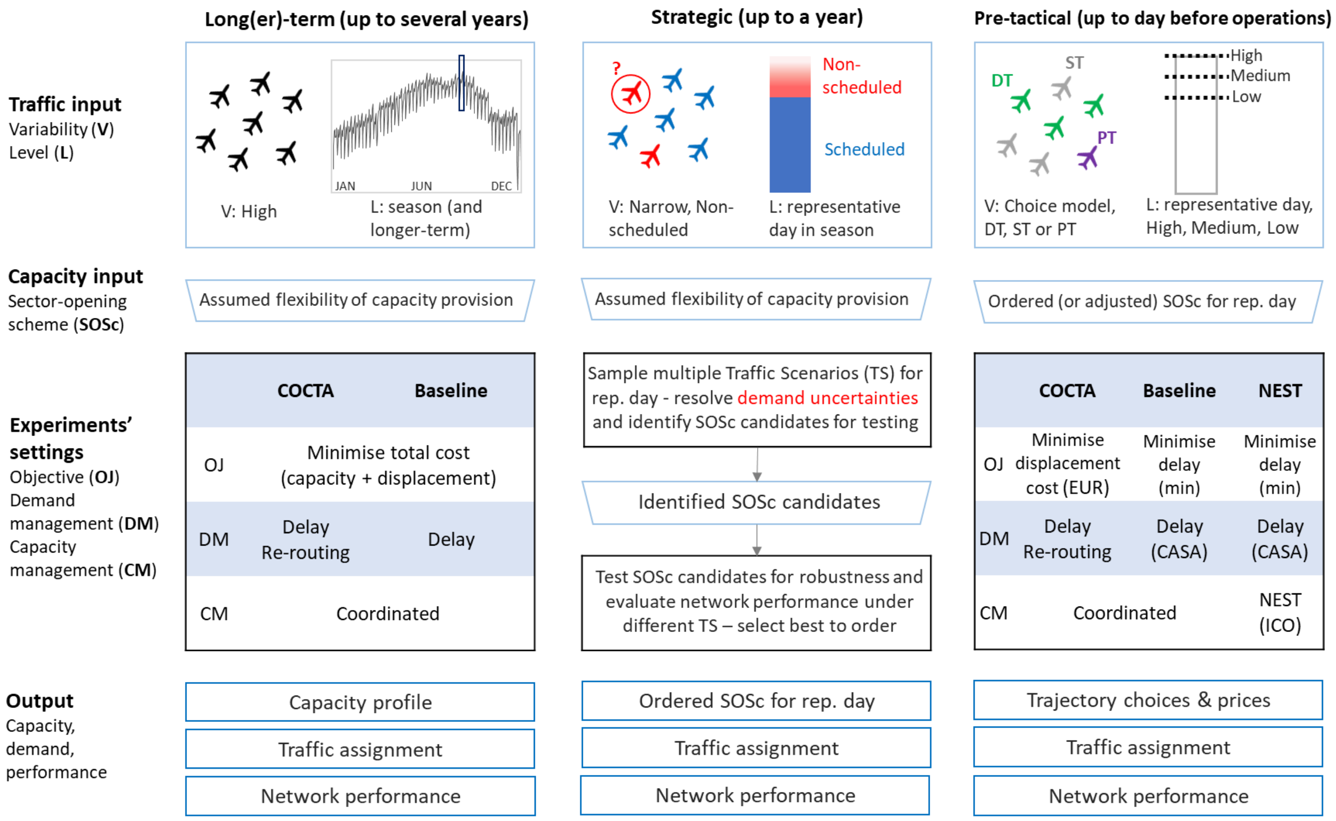

Figure 6. COCTA model testing and comparison at different timeframes (long-term, strategic and pre-tactical)

2.3.3.3 Data for model testing

We use real world data, obtained from EUROCONTROL's service Demand Data Repository (DDR2) using EUROCONTROL Network Strategic Tool (NEST).

The large-scale case study includes airspaces in Central and Western Europe, covering eight ANSPs and 15 ACCs/sector groups[5]. The COCTA concept is primarily developed for the en-route airspace and therefore, most of the selected ACCs provide ANS services primarily in the upper airspace. We choose between configurations that were used by ACCs in 2016 and select those that were most frequently used. We select configurations with different number of sectors: in total, we have 173 different configurations for 15 ACCs/sector groups.

The ANSP cost data used in the model is based on cost and capacity information provided in the ACE benchmarking report [35]. Since some ANSPs in our case study changed their sectorisation over the last years (which also has an influence on costs per sector hour), we only use the most recent data available (2015). For each 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

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[5] For instance, Karlsruhe UAC is divided into four sector groups: East, West, South and Central, each with its own sectorisation and sector opening scheme. For more details, refer to [14].

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 challenging set of flights, the busiest day on record in 2016 - 9th September, with a total of 34,594 flights in the European airspace, was chosen for the case study. In the COCTA context, the ANS charging scheme favours shortest routes, therefore, we first generate shortest routes for the traffic sample (many flights have already filed shortest plannable routes). We then generate alternative trajectory options, both in horizontal and vertical plane, crossing different elementary sectors. In the end, the final traffic sample consists of 11,211 individual flights, plus 49,685 additional (spatial) trajectory options. We also consider several levels of delays (e.g. 5, 10, 15, etc. with maximum delay of 90 minutes) for flights as well, thus further increasing number of different 4D flights. We consider delays only for shortest routes, i.e. we apply only one demand management measure per flight (delay or re-routing). To estimate delay and re-routing costs per aircraft type we make use of findings presented in [20] and [36]. 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 [19].

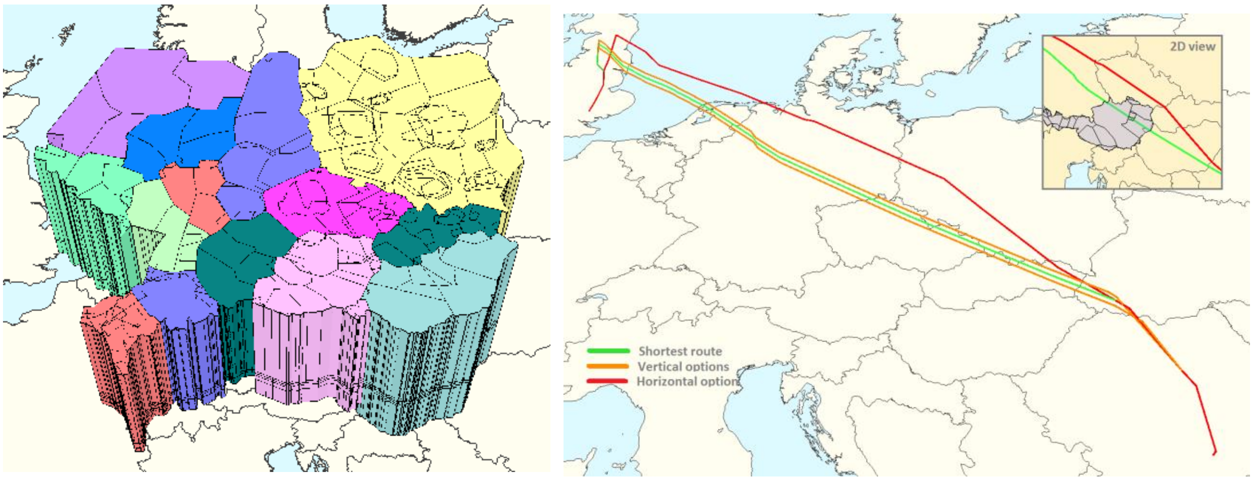

Figure 7. Case study airspace (left) and different trajectory options (right)

2.4 Key Project Results

We present some of the key project results for each stage of model testing, as indicated in the previous section.

2.4.1 Long-term capacity ordering

We start with the individual results of several hundred iterations, which correspond to different traffic materialisations, uniformly distributed between “low” (8,300) and “high” (11,211) demand in the network. The number of flights in the COCTA and the Baseline scenario does not differ, since we are using the same demand across scenarios, which ensures fair comparison between them.

When demand in a given network is below 10,000 flights, there is no big difference between capacity needed for COCTA and for the Baseline scenario, which is not surprising, since both scenarios use the same model. However, when demand in the network is higher than that, COCTA performs significantly better, both in terms of less capacity needed for the same demand levels, but also in less flights being displaced (Figure 8).

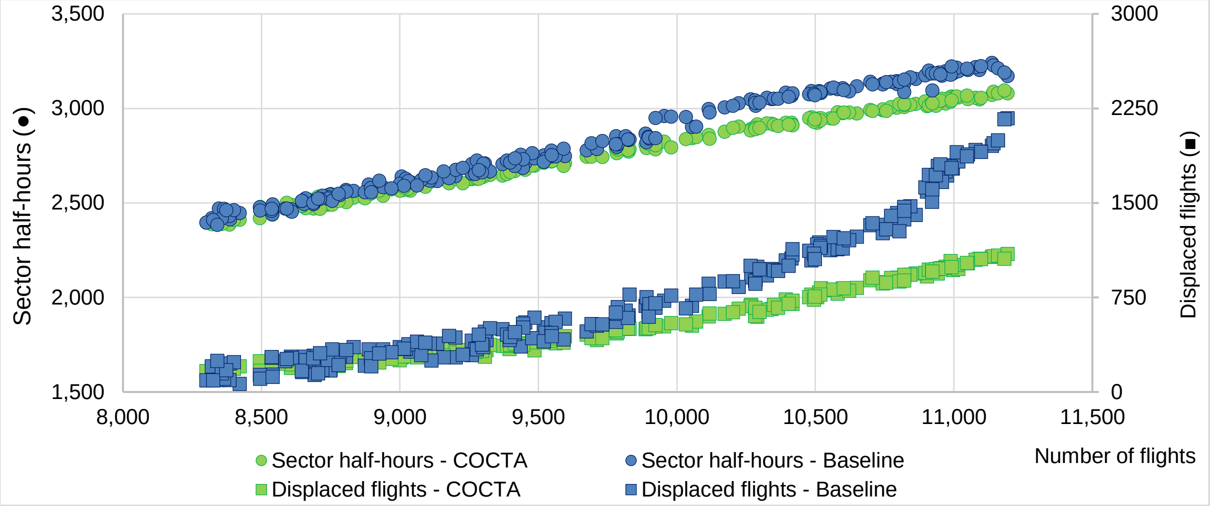

Figure 8. Capacity required and displaced flights comparison between Baseline and COCTA

Moreover, the Baseline scenario uses configurations with more sectors open than COCTA, as illustrated in Figure 9.

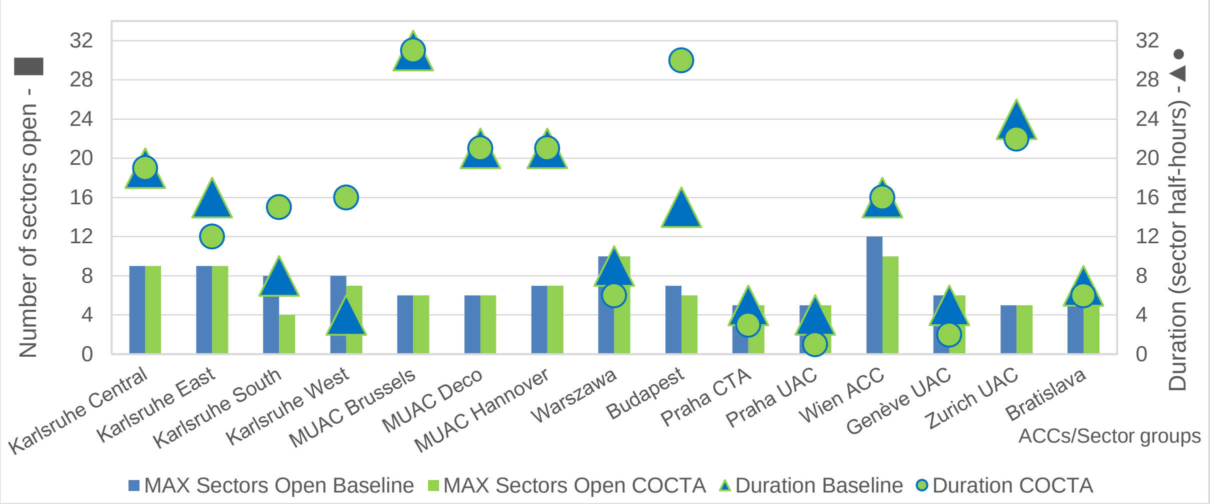

Figure 9. Maximum sectors open and duration (sector half-hours) at maximum configuration

In the Baseline scenario, flights are predominantly delayed, with only minor re-routings (up to 2NM) to avoid delays higher than 90 minutes, which we set as a maximum delay allowed for this stage. Even with minor re-routings allowed, delays in the Baseline scenario start increasing in a non-linear fashion when demand exceeds 10,000 flights, due to local capacity bottlenecks. The equity indicator for very long delays also heavily favours systematic and centralised application of re-routings, as there are no severely delayed flights in the COCTA scenario, (Figure 10).

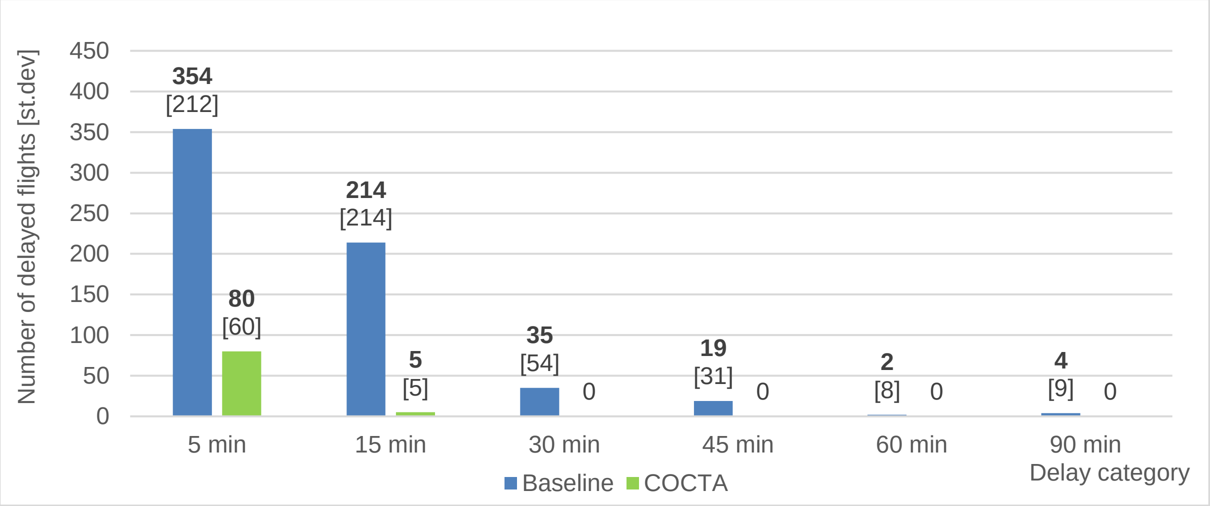

Figure 10. Average number of delayed flights per iteration, per delay category [st.dev]

In this case of very high delays, the Baseline scenario is not a realistic representation of demand materialisation, but merely a consequence of limited capacity in the network and limited demand management actions at the strategic stage. The COCTA mechanism makes far more frequent use of spatial displacement (re-routings), with about 450 re-routed flights on average (=531 displaced minus 85 delayed flights), corresponding to 4.6% of all flights. Consequently, the CO_2 emission due to additional mileage is notably higher in the COCTA scenario. The distribution of spatial deviations from the shortest plannable route in the COCTA scenario is however strongly right-skewed, with re-routings being up to 7.5NM for 75% of all re-routed flights, and up to 30NM for 99% of all re-routed flights (Figure 11). Maximum re-routing length allowed is 50NM, with only 100 flights, counting together across all 200 iterations, being re-routed more than 45NM.

Figure 12 shows that the cost-efficiency performance of the COCTA and the Baseline scenario is broadly comparable for low and moderate demand volumes, i.e. until about 10,000 flights. For higher demand materialisations total cost in the Baseline scenario starts increasing in a non-linear way, whereas in the COCTA scenario the linear relationship between traffic volume and total costs continues. The cost-efficiency gap between the two thus increases with the demand increase, owing primarily to dramatic growth in the displacement costs in the Baseline scenario. This again is a consequence of the range of demand management measures available in the Baseline scenario, and of strong non-linearity of at-gate delay costs (Cook and Tanner, 2015), especially for delays in excess of 30 minutes, which are far more frequently imposed in the Baseline scenario, (Figure 10).

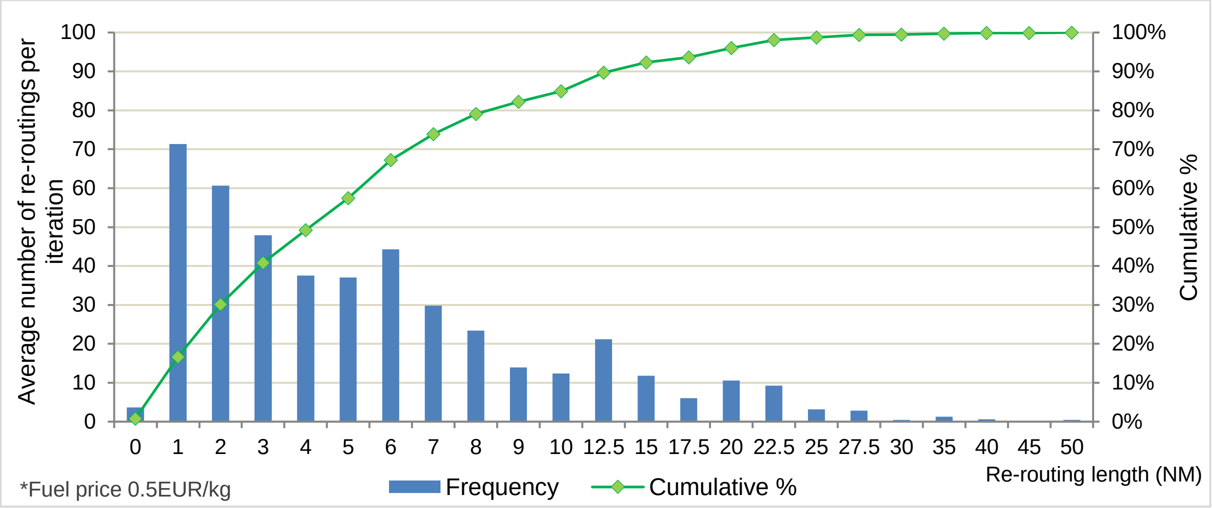

Figure 11. Average number of re-routings and distances per iteration (COCTA scenario)

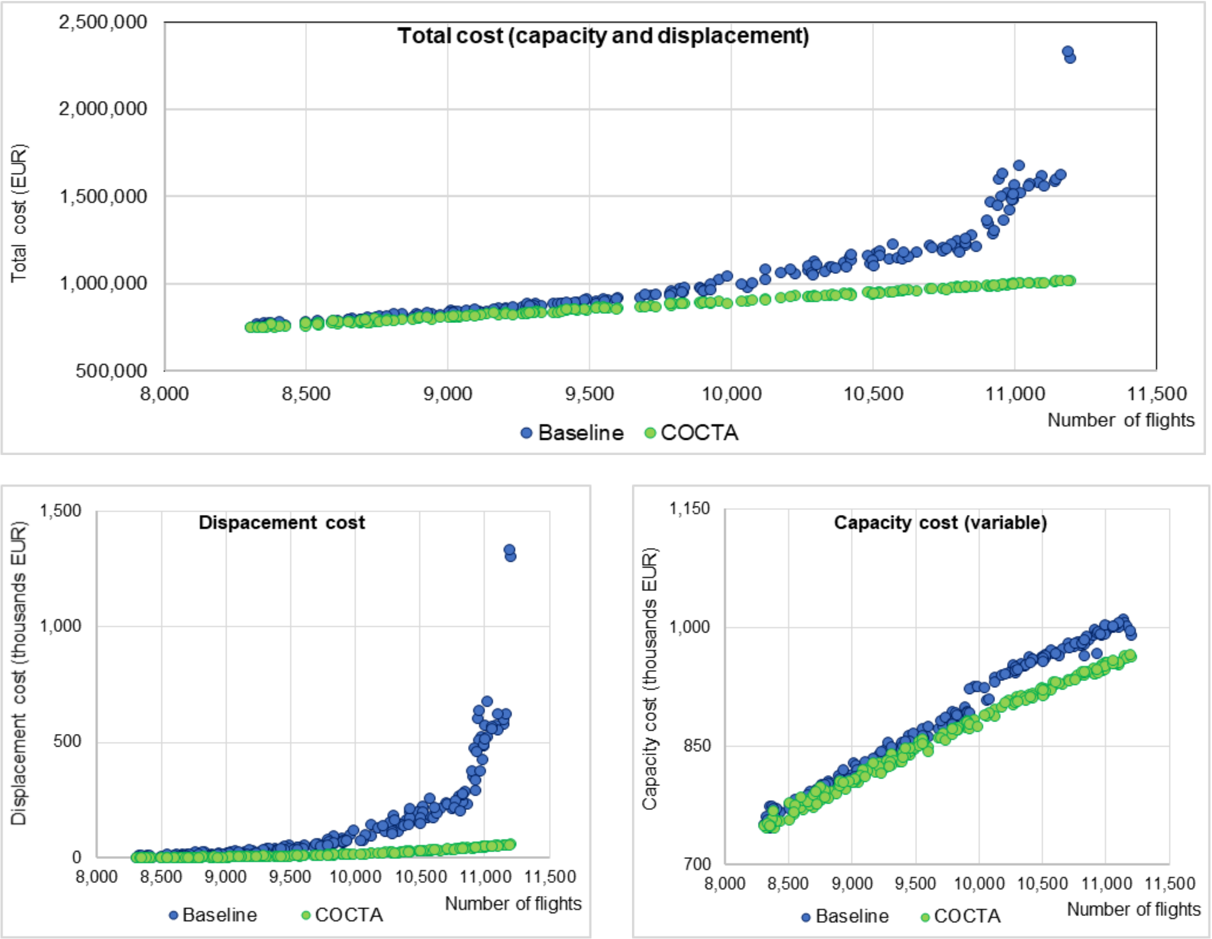

Figure 12. Comparison between Baseline and COCTA total cost-efficiency (capacity and displacement

The analyses so far compared the COCTA and the Baseline scenario over a wide range of demand levels expected to materialize in the network during a schedule season (and/or years), accounting for a high level of traffic variability (in terms of number of flights and spatio-temporal distribution). This serves as a starting point for the NM to assess required capacity profiles during the season, or even for a longer period, for all ACCs. We observe a very strong correlation between the number of flights and almost all the other variables (KPIs) monitored, usually higher than 0.9. This indicates that the number of flights is a very strong driver and predictor not just for the capacity required in the coming period (see Figure 8) but also for the overall network performance. The NM, therefore, can base its capacity orders, even in the long term, upon the expected traffic growth in the network. Potentially, the NM could conclude that some ACCs might need to increase their maximum number of sectors or provide the maximum capacity level for a longer period. Since we don't have reliable information on the current "limits" for maximum capacity levels and for how long they can be provided by each ACC, we cannot test and evaluate if that is the case.

2.4.2 Strategic capacity ordering

2.4.2.1 Scenario identification

To demonstrate capacity ordering decisions taken by the NM, that is, sector-opening schemes for ACCs, we use a representative day in the network. We consider a moderate level of traffic variability, i.e. assume that all scheduled flights will materialize as planned, with only a portion of demand (non-scheduled) being "stochastic". We demonstrate this process for a busy Friday traffic (pattern), anticipating that the total number of flights will be 11,000 including ± 2% traffic variability. Out of 11,000 flights, approximately 85% are scheduled (and deterministic), while we assume that variability, again in terms of traffic levels and spatio-temporal distribution in the network, originates from the remaining 15% of non-scheduled demand.

Based on model output (active sector configurations over time per each ACC) for several hundred runs of the model, within a relatively narrow range of high demand materialisations, we obtained the distribution of SOSc for each ACC for the entire day. Building upon obtained sector-opening schemes for each ACC for each 30-minute time window (48 periods in the day), we defined four representative SOScs to be used for the second stage analysis, i.e. for the strategic scenario testing:

- MIN: representing the sector-opening schemes providing as low as possible capacities which still, on average, allows for accommodating the expected demand.
- Q1: broadly corresponding to the first quartile (25th percentile) of the capacity provided per each ACC and each 30-min period. This is a slightly more generous capacity-policy than MIN, expected to result in higher costs of capacity provision but also improved delay and environmental performance, on average.
- MEDIAN: broadly corresponding to the median (50th percentile) of the capacity provided per each ACC and each 30-min period, aiming to broadly represent an "average" case.
- MAX: Meant to reflect the most 'conservative; capacity policy, taking for each ACC and each 30-min period the maximum observed number of opened sectors. This arguably mimics planning for the highest-demand scenario, with likely redundancies in some ACCs. It is thus not intuitively clear if (or how often) gains from reduction of displacement costs would offset the higher capacity provision costs.

In Table 2, we present the network performance results, which correspond to generated SOSc. It should be noted that the difference between the MIN and MAX scenario is 167.5 sector-hours, that is, MAX SOSc provides, overall, 11.7% more sector-hours than the MIN SOSc (Table 2). Furthermore, MAX adds 6 more sectors opened at maximum configuration compared to MIN, which might also have longer-term cost implications.

Performance indicators	SOSc scenario			
	MIN	Q1	MEDIAN	MAX
Capacity (sector-halfhours)	2,873	2,974	3,062	3,208
Sum of peak ACC configurations (sectors)	94	96	99	100
Feasibility	0.65	0.95	1	1
Variable capacity cost	902,520	933,166	957,516	998,004
Average capacity cost per flight (EUR)	81.6	84.3	86.5	90.1
Average total cost per flight (EUR)	117.2	95.7	91.7	95.1
Displacement cost (EUR) [st.dev]	394,866 [187,081]	126,901 [99,572]	57,877 [5,482]	55,678 [4,091]
Number of displaced flights [st.dev]	1,233 [118]	1,072 [61]	1,074 [55]	1,041 [53]
Total delay (min) [st.dev]	6,961 [3,132]	2,423 [1,806]	1,201 [126]	1,208 [103]
Average delay per flight (min) [st.dev]	0.63 [0.28]	0.22 [0.16]	0.108 [0.011]	0.109 [0.009]
Average delay per delayed flight (min)	17.4	9.3	5.82	5.79
Average number of flights delayed 15-30 (min)	102.2	34.3	16.1	16.5
Average number of flights delayed 45+ (min)	68.8	15.9	0.2	-
Extra CO2 (kg) [st.dev]	168,393 [28,500]	130,900 [21,665]	119,852 [8,896]	115,720 [7,542]

Table 2. COCTA scenario identification for a representative day

With the MIN SOSc we get 35% of unfeasible solutions, meaning that there are 35% demand materialisations which cannot be accommodated by such SOSc when a maximum at-gate delay of 90 minutes is assumed. With the Q1 SOSc 5% of the demand profiles turn out to be too challenging for the available capacities and the predefined range of available demand management actions, Table 2.

Whereas there is quite a sharp performance improvement between the MIN and the Q1 SOSc, in particular concerning total delay, incidence of lengthy delays and the CO_2 emissions, the improvement gradient notably slows down between the Q1 and MEDIAN SOSc, and effectively diminishes between the MEDIAN and the MAX SOSc, except for slight CO_2 emission reduction (Table 2).

With MEDIAN and MAX SOSc we get feasible solutions for every random demand sample, the summary results of which are presented in Table 2. The MEDIAN SOSc spends a 4.8% lower overall capacity than the MAX SOSc.

With respect to total cost-efficiency (capacity and displacement cost), we can clearly observe the improvements from MIN to Q1 and MEDIAN, owing to larger decline in displacement cost than increase in capacity cost (Figure 13). Adding more capacity to MEDIAN in this case leads to a further decrease in displacement cost, but at the expense at higher total cost, due to higher cost of capacity provision (Figure 13).

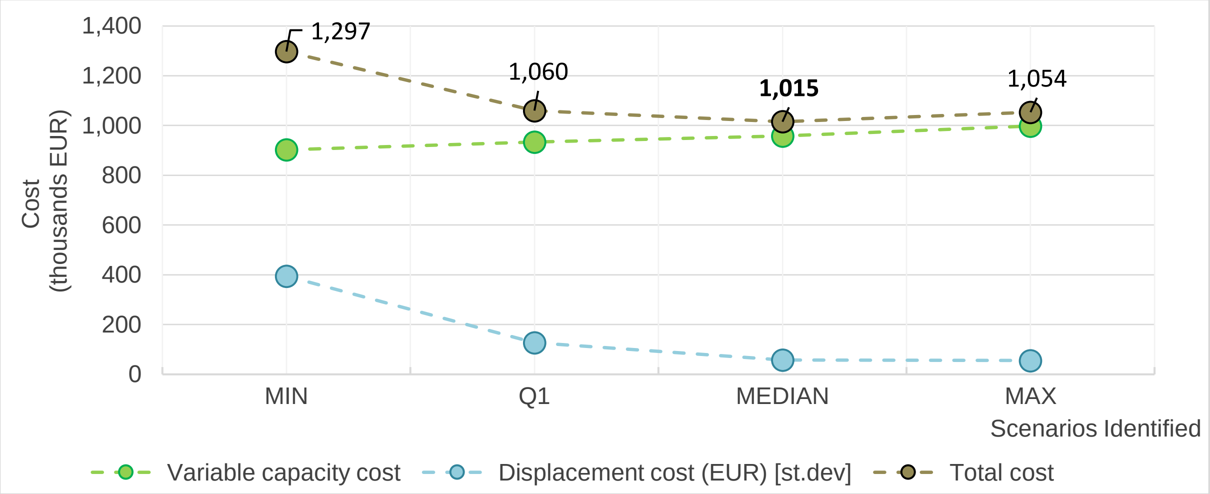

Figure 13. Capacity and displacement cost trade-off between different scenarios

2.4.2.2 Scenario testing

Based on the results from the Scenario Identification step, we proceed with testing and evaluating in more detail only the MEDIAN and the MAX sector-opening schemes, since those were able to accommodate all flights in each iteration. In this step, the NM assesses fixed sector opening schemes (MEDIAN and MAX) for each ACC, for the same traffic levels and assumed variability in the SI step. Again, we run several hundred iterations, with different non-scheduled traffic materialisations in the network, and summarize our results in Table 3.

Table 3 suggests that the MEDIAN SOSc, on average, performs 3.6% better than the MAX scenario in terms of total cost (variable cost of capacity provision plus displacement cost) and that the difference is statistically significant (Mann-Whitney U Test p=.000[6]). This is because the increment in displacement costs, owing to scarcer capacity in MEDIAN, is on average lower than the corresponding cost of additional capacity provided in the MAX SOSc. On the other hand, there is no significant difference between displacement cost in MEDIAN and MAX scenarios at 5% level (Mann-Whitney U Test p=0.070).

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[6] Since the results (data) are not normally distributed (Kolmogorov-Smirnov and Shapiro-Wilk tests) and variances are not the same (Levene's test for equality of variances), we use non-parametric Mann-Whitney U test [44] to thoroughly compare network performance between the two. As a note, non-parametric test generally have lower power for statistical inference compared to parametric tests (like t-test); for instance, when the alternative hypothesis is true, non-parametric tests may be less likely to reject the null hypothesis [44].

Performance indicators	MEDIAN			MAX		
	Moderate	High [St.dev]	Very-High	Low	Medium [St.dev]	High
Number of flights in the demand scenario	10,856	11,075 [0]	11,176	10,856	11,075 [0]	11,176
Total cost (capacity + displacement) [EUR]	1,004,890	1,015,393 [5,482]	1,029,210	1,044,590	1,053,682 [4,091]	1,058,120
Capacity cost (only variable) [EUR]	957,516	957,516 [0]	957,516	998,004	998,004 [0]	998,004
Displacement cost (EUR)	47,371	57,877 [5,482]	71,693	46,590	55,678 [4,091]	60,121
Total number of sector half-hours used	3,062	3,062 [0]	3,062	3,208	3,208 [0]	3,208
Number of displaced flights	950	1,074 [55]	1,152	922	1,041 [53]	1,105
Number of delayed flights	176	206 [15]	234	174	209 [16]	233
Total delay (min)	990	1,201 [126]	1,565	1,000	1,208 [103]	1,375
Average delay per flight (min)	0.091	0.108 [0.011]	0.140	0.092	0.109 [0.009]	0.123
Average delay per delayed flight (min)	5.50	5.82 [0.23]	6.69	5.49	5.79 [0.11]	5.94
Num of flights delayed 5 min	161	190 [12]	205	174	192 [13]	233
Num of flights delayed 15min	9	16.0 [3.5]	25	9	16.4 [3.1]	21
Num of flights delayed 30min	0.0	0.1 [0.45]	2.0	0.0	0.05 [0.22]	1.0
Num of flights delayed 45min	0.0	0.1 [0.31]	1.0	0.0	0.0 [0.00]	0.0
Extra CO_2 emitted (kg)	101,323	119,852 [8,896]	135,294	98,678	115,720 [7,542]	123,478

Table 3. Scenario testing: network performance for COCTA MEDIAN and MAX SOSc

The remaining indicators are, on average, typically only marginally better in the MAX scenario than in the MEDIAN, with however somewhat higher dispersion of values (measured via standard deviation) in the MEDIAN scenario, which is expected given the scarcer capacity, owing to the impact of most challenging demand materialisations. The capacity decision of the NM depends on its objective function. If the NM is supposed to minimize overall costs, the MEDIAN scenario should be chosen. However, if a very strong emphasis is put on some other KPIs, e.g. minimizing CO2 emissions, the MAX scenario might be preferable.

2.4.3 Strategic to pre-tactical demand management

Network performance achieved at the strategic stage is the system optimum, since the NM assigns trajectories as a central planner. However, from strategic to pre-tactical stage, AOs choose trajectories and might deviate from this system optimum. Therefore, the NM defines trajectory products and prices thereof, to steer demand distribution in the network to minimise (maintain) total cost to AOs: cost of capacity (which is sunk at this stage) and cost of delays and re-routings (displacement cost).

Figure 14 compares total delay at strategic stage, based on the NM optimal trajectory assignment, and delay at pre-tactical stage, based on AOs trajectory choices. With different trajectory products and their prices, for assumed AO choice model, the NM is able to maintain optimal delay within 10-15% margin.

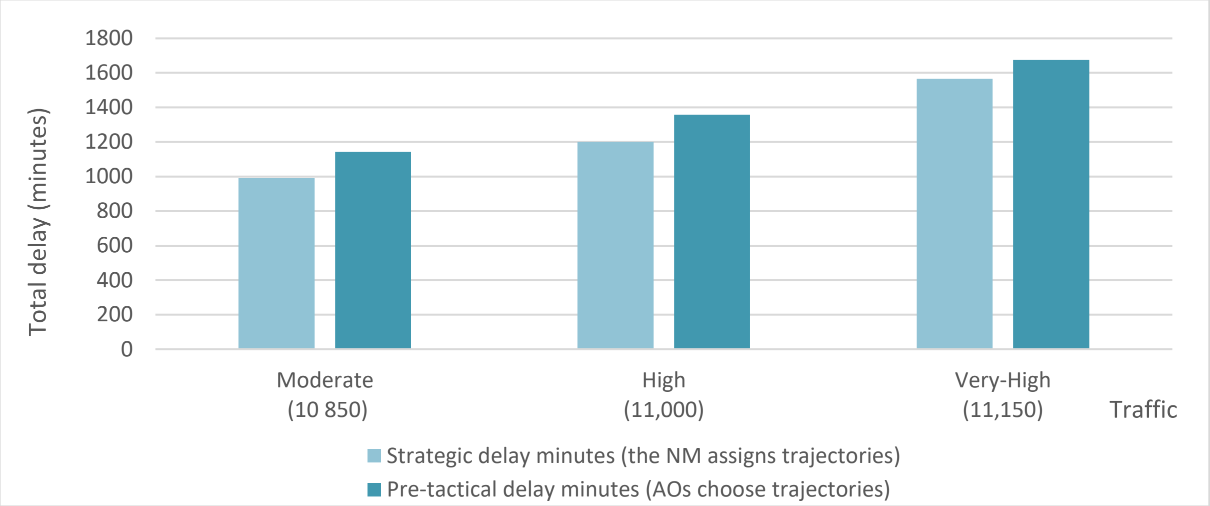

Figure 14. Average total delay for different traffic levels: strategic vs. pre-tactical

On the other hand, with price incentives and different trajectory products, the NM is able to reduce additional CO_2 emissions due to re-routings (Figure 15).

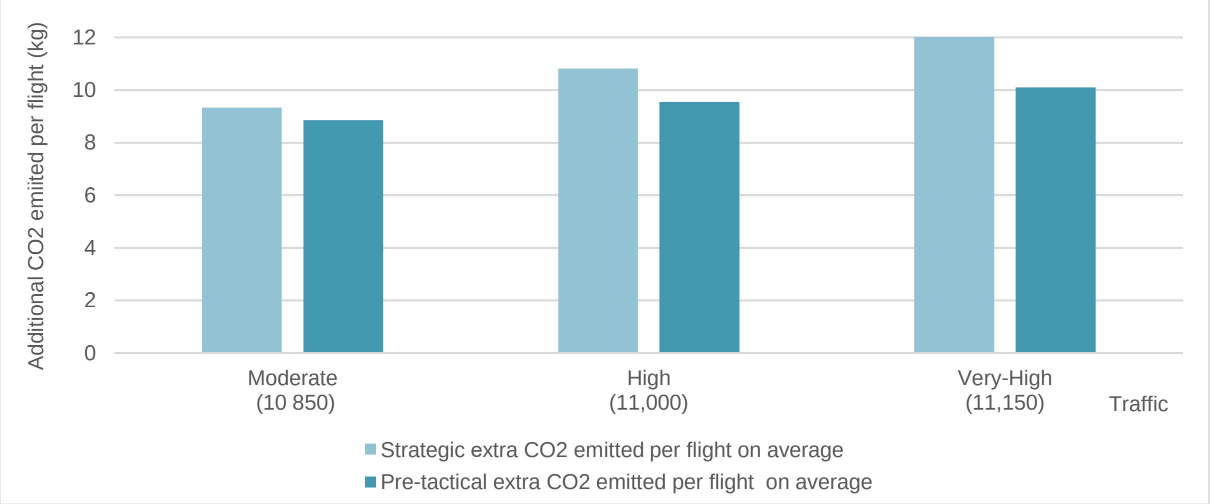

Figure 15. Average extra CO_2 emission per flight for different traffic levels: strategic vs. pre-tactical

Moreover, the NM is able to make average estimated displacement cost at strategic level almost equal with the total incentives offered to AOs to accept trajectories which might be subject to delays or re-routings Figure 16.

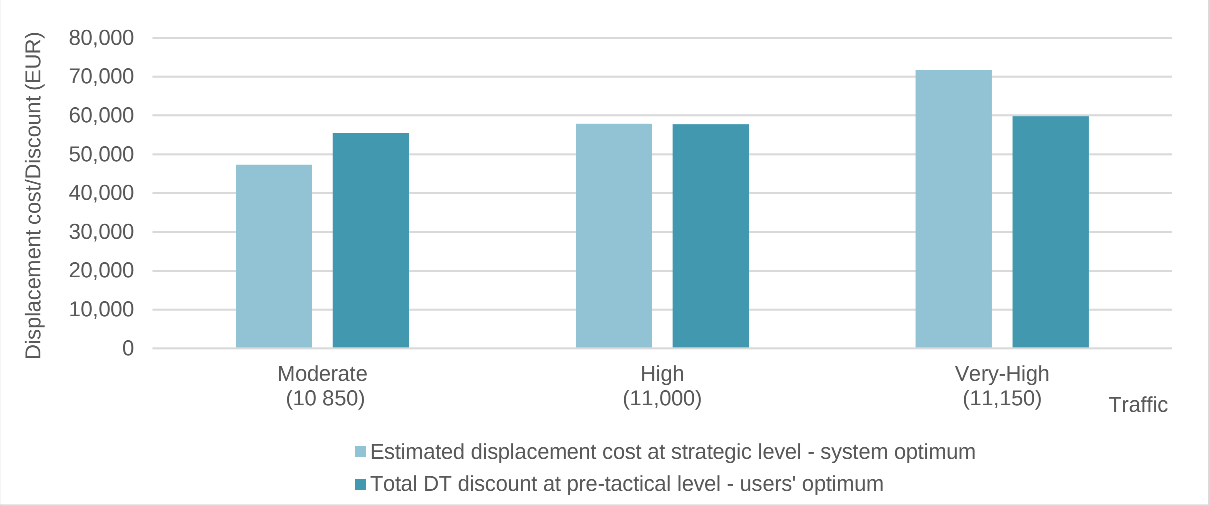

Figure 16. Estimated displacement cost at strategic stage vs aggregated DT discount at pre-tactical stage

Lastly, we compare the network performance between COCTA, the Baseline and the NEST scenario when demand is at its maximum level considered in the case-study, that is, 11,211 flights[7].

The results, shown in Table 4, indicate that NEST uses 10% less sector hours compared to COCTA and the Baseline with MEDIAN SOSc scenarios, but is comparable to COCTA MIN SOSc scenario (difference in sector-hours is less than 0.1%). However, NEST opens slightly more maximum configurations compared to COCTA and Baseline scenarios.

The NEST scenario generates the highest total delay of the four scenarios (66,112 minutes), with, importantly, 474 flights heavily penalized (delays from 60 to 130 minutes). In turn, this generates very high delay per delayed flight (nearly 50 minutes/flight) and average delay per flight (almost 6 minutes/flight).

The Baseline scenario, which also exclusively uses delays as demand management measure was not able to find a feasible solution with delays limited to 90 minutes (we did not test the case with delays up to 120/30 minutes, as is the case of the NEST scenario). Therefore, the experiment design was modified to allow re-routings, once delays have been assigned, so as to obtain a feasible solution. In such case, re-routings become severe: in total 485 flights were re-routed with average re-routing length of almost 20NM per re-routed flight (9,420NM in total). In the end, the Baseline scenario generates almost 30% less delay minutes compared to the NEST, with somewhat higher number of delayed flights and better delay distributions (right skewed) compared to the NEST scenario.

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[7] It is very time consuming to run experiments with NEST with varying level of demand, therefore the decision to use only the maximum demand for comparison purpose.

Performance indicators	Scenario (SOSc)			
	Baseline (MEDIAN)	NEST	COCTA (MIN)	COCTA (MEDIAN)
Number of flights in the demand scenario	11,211	11,211	11,211	11,211
Total number of sector half-hour used	3,063	2,854	2,876	3,063
Sum of maximum sectors open	99	101	94	99
Number of displaced flights	2,067	1,374	1,353	1,136
Number of delayed flights	1,582	1,374	415	258
Total delay (min)	48,175	66,112	7,953	1,470
Average delay per flight (min)	4.3	5.9	0.71	0.13
Average delay per delayed flight (min)	30.45	48.12	19.11	5.69
Num of flights delayed 5min ***[0min, 5min] for NEST***	329	131	218	240
Num of flights delayed 15min ***[5min, 15min] for NEST***	400	372	68	18
Num of flights delayed 30min ***[15min, 30min] for NEST***	349	271	45	2
Num of flights delayed 45min ***[30min, 45min] for NEST***	266	65	57	0
Num of flights delayed 60min ***[45min, 60min] for NEST***	111	61	15	0
Num of flights delayed 90min ***[60min, 90min] for NEST***	127	87	11	0
Num of flights delayed [90min, 130min]	0	387	0	0
Average re-routing per flight [NM]	20	0	11.48	7.90
Extra CO_2 (kg)	190,049	0	203,820	125,506

Table 4. Netwrok perfromance achieved at pre-tactical level for different scenarios

With the COCTA scenario using the MEDIAN SOSc the resulting delay is by far the lowest of all: 1,470 minutes in total. Moreover, there are no long delays in the COCTA scenario, which means that delayed flights will be far less likely to generate reactionary delays (which in case of very long primary delays cannot be mitigated). Since re-routings are considered alongside with delays (on cost basis), this scenario outperforms the Baseline both in terms of delays and re-routings. Within the COCTA MEDIAN scenario, there are 878 flights re-routed on average by 7.86NM and a total of slightly less than 6,950NM. Since COCTA generally re-routes smaller aircraft, as that is more cost-efficient than re-routing larger aircraft, the carbon footprint is also much lower compared to the Baseline scenario. Note also that in COCTA scenario we still rely on AO choices, that is, the choice model is "active" and the NM still employs discounts to drive AO's behaviour towards system optimum. However, even in this case, the NM is able to keep the "system optimum" network performance with trajectory price incentives (total discount compared to total displacement cost). There is only a relatively small and stable variation in results and the NM can adjust the product prices for given choice model parameters.

Since the COCTA MIN SOSc happens to have the capacity budget similar to that of the NEST scenario, we decided to test the COCTA MIN SOSc scenario too, and see to which extent there are differences between the two scenarios in other performance areas. It should be noted that we had to allow for a very long computational time to be able to obtain feasible solution with this very scarce COCTA capacity budget.

The results suggest that the COCTA MIN SOSc scenario strongly outperforms the NEST scenario in terms of total delay and the incidence of lengthy delays, with however inevitable penalty in terms of CO2 emissions, corresponding to extra fuel burned of 5.8 kg/flight.

Finally, an interesting comparison can be made between the COCTA MIN SOSc and the Baseline MEDIAN SOSc scenarios (Table 3). It reveals that the COCTA mechanism is able to simultaneously reduce the capacity wastage (by consuming 6.1% fewer sector-hours), total delays (by saving more than 40,000 delay minutes), and the incidence of long delays (with 26 flights delayed 60-90 minutes compared to 238 such flights in the Baseline), while only marginally deteriorating the environmental performance (13.8t higher CO2 emission than in the Baseline, corresponding to an increase in fuel burn of 0.39 kg/flight on average). In terms of re-routing lengths, 938 flights are re-routed on average 11.48NM, which makes a total of 10,772NM (higher than MIN, but more evenly distributed).

2.4.4 Strategic to pre-tactical demand management: introduction of a new trajectory product

Based on recommendations received from stakeholders, Aircraft Operators (AOs) in particular, we introduce a new trajectory product. To increase the acceptance by AOs, it was suggested that a new trajectory product - Premium Trajectory (PT) – shall be introduced, in addition to the two trajectory products already defined in previous COCTA deliverables Standard Trajectory (ST) and Discounted Trajectory (DT).

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 network manager (NM) retains the right to decide shortly prior to the departure day which trajectory exactly will be flown (within agreed margins). The only difference is that the margins (spatial or temporal) for DT are wider than for ST, and hence DT will be offered at a discount. PT, however, has a quite different structure. Since it is now the AO who has the right to decide on a trajectory shortly prior to departure, it introduces a higher level of uncertainty on the capacity side. The NM has to account for this additional source of uncertainty in the capacity management (ordering) process at the strategic level.

Alongside introducing a new trajectory product, we propose a new solution approach to solve the COCTA model when using large-scale examples (a more efficient approach). We do not reproduce the formulae here (refer to the COCTA deliverable D5.4); instead, let us briefly outline the main changes between the above version and the one put forward in our working paper. The underpinning idea stays the same; however, we discovered that we can write both master and sub-problem in an equivalent but more efficient form. Both problems can be stated in a way such that their constraint matrices have a certain structure (called "totally unimodular") that guarantees that we can relax the integer constraints on the decision variables whilst still obtaining an optimal integer solution. This has huge advantages on runtime since it is much more computationally expensive to solve discrete optimization problems than continuous ones.

We test this approach on a case study involving Central European airspaces and over a thousand flights during a one-hour time period. Our main objective is to quantify the impact of allowing AOs to choose their own trajectories (i.e., the PT product). It is intuitive that this will have detrimental effects on overall cost performance, but it is unclear how severe these effects will be, and to what extent we can remedy the situation by targeted selling of DT products.

We use the same dataset, with the difference that we select flights based on their last filed flight plans, which cross the selected airspace between 10 and 11 AM. In total, we have 910 scheduled flights that are considered fixed in our network in all scenarios. Out of all non-scheduled flights on that day, we select those that cross the selected airspace at any time (1,569 in total). Since we test the model for 10-11 AM period, we change their airspace entry times from the original flight plan to a time uniformly sampled over the selected period. Each traffic scenario is created by uniformly sampling a subset of 160 from this set of 1,569 flights and adding them to the set of scheduled flights. We create 100 traffic scenarios in this manner. Flights can be either delayed or re-routed (only one demand management measure per flight) to improve total cost-efficiency subject to hard capacity budget constraints. Delay options are discrete and the same for each flight, namely 5, 15, 30 or 45 minutes. Each flight has a number of alternative spatial routes as well, all generated using the NEST tool. Overall, the problem is modeled over a two-hours time horizon to account for flights being delayed beyond 11:00 AM.

We test three different capacity decision policies that are defined in full detail in the deliverable D5.4:

- *AV*: in the averaging policy, the capacity decision is obtained by averaging the capacity order decision h_a^F for airspace a and scenario F (that results from the foresight approach) across all scenarios.
- *Eps-5 / Eps-20*: In the risk-based policy, the capacity decision is obtained by setting h such that the sample probability of encountering a flight scenario in which we had better planned for more capacity in at least one airspace is less than a given epsilon (set to either 5% or 20%), where the sample probability distribution of h has been computed by the perfect foresight approach.

In each simulation run, we start in stage 1 (strategic) with obtaining the capacity budget h using a given decision policy as well as prices for DT, ST and PT. In stage 2 (pre-tactical), we sample the actual traffic materialization and trajectory product choices of the AOs. This serves as an input to the optimization of demand management decisions, as well as the sector opening scheme subject to the available capacity budgets. We repeat the simulation 200 times and report average results.

To assess the effect of granting AOs who purchase the PT product the permission to decide themselves on their trajectory, we consider two scenarios. In the first, we assume that all flights that chose PT have a random trajectory assigned to them that is not under the influence of the NM. In the second scenario, we assume that the NM can still assign PT flights to all routes incorporated in the range of route options for ST. The latter scenario could represent the case of asking late-arriving trajectory requests to pay a surcharge whilst not granting them additional benefits over ST. In our simulation, all non-scheduled flights (that often would not be able to book a trajectory in advance) and only on average about 2% of scheduled flights select PT.

Policy	Capacity cost	Displacement cost	Total cost	Avg (#non-assigned flights)	#flights
AV	51,854	205,447	257,301	0.07	1,070
Eps-20	57,808	196,783	**254,591**	0.00	1,070
Eps-5	61,877	196,760	258,637	0	1,070

Table 5. Average costs when PT flights may choose their own trajectory

In Table 5, we see that the total cost (capacity cost plus displacement cost) is minimized for the most risk-averse policy Eps-20. Moreover, this policy also always procured sufficient capacity to accommodate all 1,070 flights. The displacement cost is three to four times the capacity cost depending on our decision policy, which suggests that substantial demand management measures are being applied to serve all flights within the given capacity limits.

Now compare this to the situation where the NM retains decision power over flight trajectory assignments (even for PT) in Table 6.

Policy	Capacity cost	Displacement cost	Total cost	Avg (#non-assigned flights)	#flights
AV	51,854	6,544	58,398	0.02	1,070
Eps-20	57,808	661	58,469	0.00	1,070
Eps-5	61,877	627	62,504	0.00	1,070

Table 6. Average costs when PT flights are assigned a trajectory option like for ST

In this case, displacement costs are nearly non-existent for the risk-based policies. The capacity costs are exactly the same in both scenarios since they are not affected by our differing assumptions regarding PT. Therefore, the ability to retain the power to assign flights to trajectories from the ST range of options even for PT has a huge effect on displacement cost reduction. This is in line with our earlier findings in the deliverable D5.3 that the COCTA mechanism has the potential to greatly reduce demand management-related costs.

The risk-based policy Eps-20 again performs best in that it produces the lowest cost (on par with AV) and accommodates all traffic within its ordered capacity. The discount under the given choice models was calculated in all scenarios to be 25% relative to the ST charge.

Cost recovery is roughly achieved: as reported in Table 7 the AV policy generates income slightly in excess of the capacity costs incurred, whereas the risk-based policies Eps-5 and Eps-20 both generate slightly less. Overall, costs and income are within a few percentage points of each other.

Policy	Total income	#DT	#ST	#PT	Income from DT	Income from ST	Income from PT
AV	53,049	444	444	182	17,763	23,653	11,634
Eps-20	55,856	444	444	182	18,702	24,904	12,249
Eps-5	58,881	444	444	182	19,716	26,253	12,913

Table 7. Income generated when PT flights are being assigned a trajectory from ST set

The situation is nearly the same when PT flights are allowed to choose their own trajectory as shown in Table 8.

Policy	Total income	#DT	#ST	#PT	Income from DT	Income from ST	Income from PT
AV	53,044	445	443	182	17,783	23,619	11,642
Eps-20	55,850	445	443	182	18,724	24,868	12,258
Eps-5	58,876	445	443	182	19,738	26,215	12,922

Table 8. Income generated when PT flights can choose their own trajectory

We have worked on a medium-scale case study because of time constraints; whilst the solution approach that we propose in the deliverable D5.4 is scalable (as demonstrated therein), running it over hundreds of simulations is still time-consuming. Nevertheless, even on the scale of about a thousand flights we can clearly observe the effect of allowing greater flexibility to airspace users; in our context, allowing non-scheduled flights to choose their own trajectory with a premium trajectory product.

The most notable effect is on displacement costs, which includes both delays and re-routings. Namely, allowing AOs to have additional flexibility to choose trajectories, which are "non-optimal" from system's perspective, but are "optimal" from users' perspective, leaves limited options for the NM to distribute (in space in time) other flights in the network. This leads to very long delays and re-routings, and consequently, to higher estimated displacement cost. Note that this displacement cost could potentially be decreased by adding more capacity in some parts of the network, but at the expense of higher cost of capacity provision.

In other words, with capacity decisions fixed and without an option to (re)adjust it, offering premium trajectory (PT) products can be expected to lead to substantially higher displacement costs for other AOs. One should also note that the case study used to test the concept of premium trajectory has an extremely challenging demand profile for the capacity available. In a less challenging demand vs. capacity situation, the displacement cost might be much lover (yet to be tested). Moreover, the additional displacement cost decreases with a declining share of AOs choosing the PT product. This share, however, can be influenced by the NM through the trajectory pricing mechanism. In other words, if the PT product becomes more expensive, fewer airlines will purchase it and therefore displacement costs for the entire system will be reduced.

These results should also be observed in the light of the study design and information/data available. Namely, since the trajectory products still don't exist, and there is no historical purchase/AO decisions data available to estimate a credible choice model, we apply a fairly simple approach of AO decision making process (choosing trajectory products). A different choice model might have yielded somewhat different results.

Based on our limited evaluation of the new trajectory product, we can conclude that within the context of the experiment, allowing AOs to prioritise some of their flights in the network, assuming given-unchanged initial capacity order, reduces cost-efficiency. However, unlike with the other two trajectory products, the COCTA concept with additional trajectory product has not yet been sufficiently evaluated to come up with any firm conclusions. This primarily includes the currently missing impact (feedback loop in the model testing process) on the capacity ordering decision of offering a new ("premium") trajectory product. The incorporation of PT product earlier in the COCTA process and an analysis of effects on network performance in such a setting is one of the immediate areas for further investigation.

2.4.5 Stakeholder feedback

Following the recommendation from the SJU Project Officer, the COCTA team asked several experts from ANSPs, ATCOs, AOs and the NM to join the project Advisory Board (AB), five of which accepted the invitation and constituted the AB. The Advisory Board represents a nominated group of external experts-advisors who assisted in reviewing the project's development and progress as a whole and, wherever possible, contributed to COCTA's communication and dissemination activities. The Advisory Board role was to steer the project and provide a more practical-oriented feedback.

The COCTA team held several meetings with Advisory Board members and has been receiving continuous feedback on COCTA deliverables and research in general. The COCTA team held a dedicated workshop for stakeholders in Frankfurt (September 2017) and a final workshop for stakeholders in Brussels (September 2018) and documented the feedback received from stakeholders [12]. We also presented research results to the NM Director and his associates and colleagues (Brussels, May 2018), Skyguide (Geneva, July 2018) and other stakeholders. Hereby, we summarize the most important feedback received during the project, as well as some selected quotes from the industry experts.

The COCTA concept of coordinated capacity and demand management was very well accepted by all stakeholders:

- ATM experts generally agree that there is enough capacity in the network presently, but it is not provided nor made available where and when needed. The COCTA concept could be one potential solution to this practical issue. They noted that contractual relationships between stakeholders in the COCTA concept need to be further addressed and elaborated (more in Future steps section).

- ANSPs/ATCOs also had a positive feedback and stressed the importance of capacity negotiation between the NM and ANSPs, since ANSPs have "local knowledge" and more experience with sector-opening scheme needed than the NM. ATCOs also pointed out that safety assessment/analysis needs to be done for the tactical and real-time operations (which were out of the scope of the current COCTA research). Also, they stressed that ATCOs also need their plans in advance and noted that micro-management should be included in future COCTA research.

- AOs were in favour of the concept, especially for network-centric demand management actions based on incentives. From their perspective, if implemented properly, this way of managing demand may also decrease costs of flight planning in AO operation centres. They were also interested to learn how the process of trajectory negotiation, changes and updates would look like in the COCTA concept, as well as what happens if one of the contractual sides cannot deliver what was agreed upon.

Selected quotes

"The latest COCTA document [COCTA deliverable D5.3] is providing initial evidence that market and contractual approaches to supply/demand matching could be applied to ATC with clear benefits in delays, flight/environmental efficiency and cost-efficiency."
A senior ATM expert

"Think network, think cross-border, think cooperation."
CEO of an ANSP, following the COCTA presentation to stakeholders

"I remain enthused by what has been achieved so far, and I look forward to seeing how the project continues to mature during 2018."
A representative from Aircraft Operators

"I understand the proposed [COCTA] concept, everything makes sense and the only question to me is: What are the next steps and how do we bring this research to the Commission?"
A senior ATM expert following the COCTA presentation

2.5 Technical Deliverables

Reference	Title	Delivery Date[8]	Dissemination Level[9]
Description			
D1.1	Project Management Plan	18/11/2016	CO
The Project Management Plan (PMP) complements project management structure and procedures provided in the Grant Agreement Description of Action 699326 (Annex 1 Part B) and COCTA Consortium agreement. It serves as a baseline to carry out streamlined research, but also to ensure			

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[8] Delivery data of latest edition

[9] Public or Confidential

required level of dissemination and communication activities. The PMP is a live document, which is constantly being kept up to date. This deliverable contains consortium management structure and organisation, as well as assigned roles to COCTA team members. Workpackage breakdown structure to the task level is detailed in the Gantt chart. A comprehensive description of the Project Information System (PIS) is provided, as well as technical aspect thereof. Risk and issues table and detailed communication and dissemination plan are provided. The PMP has been updated several times, the last version being sent to the SJU on 11/09/18.

D1.2	Final Project Results Report	14/08/2018	PU

In this deliverable, we report the COCTA concept of the redesigned ATM value-chain in Europe with new roles and relationships between the key stakeholders: the Network Manager, Air Navigation Service Providers and Aircraft Operators. We propose a new process of establishing demand-capacity balance, as well as new approach to capacity and demand management. Such institutional and operational environment will reduce cost of capacity provision and capacity insufficiencies for Aircraft Operators, but also to performance improvements on various ATM key performance areas. This deliverable also reports other relevant aspects of the COCTA research: hypothesis, research methodology and models, data, results, stakeholders' feedback and a potential way forward, among else.

D2.1	State of the art report	08/12/2016	PU

COCTA project proposes coordinated economic measures aiming to pre-emptively reconcile air traffic demand and airspace capacity, by acting on both sides of the inequality. This document presents a review of the most relevant research efforts from the fields of Air Traffic Management, Economics and Regulation and Operations Research. We also describe the current practices employed in dealing with airspace congestion in Europe, on a strategic and pre-tactical level. The key findings from the three related areas are summarised and clear directions defined for upcoming project steps.

D2.2	Data management report	17/08/2017	PU

In this deliverable, we summarize data requirements for COCTA modelling and model testing. We present available data, that is, data sources and tools for data processing, as well as data limitations.

D3.1	ATM value-chain redesign	17/08/2017	PU

In this deliverable (D3.1) we develop a conceptual framework for the COCTA mechanism, assign roles to the different stakeholders in the value chain, and draft the process of capacity planning as well as the use of incentive schemes. The suggested process is designed in order to minimize the overall costs of capacity provision as well as costs resulting from insufficient capacity supply, provide flexibility in case of changing traffic patterns, and introduce incentives within the charging scheme that contribute to an overall efficient outcome. In addition to the process outlined above, which is based on fixed maximum capacities, we also develop ideas for coordinating long-term investment decisions by the different ANSPs. Moreover, we describe several options for the institutional framework of the Network Manager.

D4.1	Initial mechanism design	10/07/2017	PU

Building upon the framework described in COCTA D3.1 (Re-designed ATM value chain), this deliverable elaborates further detail of the process and products involved. Having condensed some

<table>
<tr><td colspan="4">key assumptions concerning the likely environment in which COCTA mechanisms would be applied, we finally synthesise an initial COCTA mechanism, expected to yield improved network performance.</td></tr>
<tr><td>D4.2</td><td>Final mechanisms</td><td>21/10/2017</td><td>PU</td></tr>
<tr><td colspan="4">This deliverable proposes the final COCTA mechanism, i.e. capacity and demand management process and measures. We refine the initial mechanism presented in D4.1 and present its elements: timeline, transactions and products and pricing options. We discuss how the COCTA team will proceed with mathematical modelling of the mechanism.</td></tr>
<tr><td>D5.1</td><td>Prototype models and small academic examples</td><td>10/07/2017</td><td>PU</td></tr>
<tr><td colspan="4">This deliverable proposes an initial mathematical formulation to be used at different stages of the COCTA mechanism. An optimization model is built upon the ideas introduced in the deliverables D3.1 and D4.1. The aim is to minimize the overall cost of capacity provision by managing airspace sectorisation over time. A small academic example is introduced to assess the model’s complexity as well as to provide a numerical analysis. Different demand distribution and capacity budget scenarios are considered, and a sequential algorithm is designed as a benchmark. The example shows that centralizing the capacity management, in combination with demand management, has a potential for significant savings within the proposed optimization model. Results of this deliverable will be fed to the following deliverables, developing more complex and realistic mathematical tools to support the final COCTA mechanism.</td></tr>
<tr><td>D5.2</td><td>Choice-based flexible product pricing model</td><td>30/01/2018</td><td>PU</td></tr>
<tr><td colspan="4">These deliverable deals with the computational challenges of incorporating trajectory pricing decisions and airlines choice behaviour into the mathematical model. A parallel is drawn from COCTA to the generic revenue management context to provide a model formulation easier to understand and test. We propose a solution approach based on the idea of re-solving a deterministic approximation of the model several times during the booking horizon. The precision and scalability of the approach is tested with examples of increasingly size.</td></tr>
<tr><td>D5.3</td><td>Choice-based joint capacity ordering and pricing model</td><td>01/08/2018</td><td>PU</td></tr>
<tr><td colspan="4">In this deliverable, we summarize COCTA innovations: changes in the Air Traffic Management (ATM) value-chain, the COCTA capacity and demand management process developed so far and COCTA mathematical models. We focus on model testing, evaluation and comparison against a baseline, using large-scale case study.</td></tr>
<tr><td>D5.4</td><td>Effects of increased flexibility for airspace users on network performance</td><td>13/11/2018</td><td>PU</td></tr>
<tr><td colspan="4">In this deliverable, we incorporate recommendations received from stakeholders, airspace users in particular. Namely, we update the COCTA model, in line with refined COCTA concept of capacity and demand management. In the refined concept airlines will be able to define their preferred trajectories and the flexibility required for each flight, as well as to decide on the final trajectory. We analyse and evaluate the effects on network performance.</td></tr>
<tr><td>D6.1</td><td>Conference paper, 6th SIDs</td><td>22/11/2016</td><td>PU</td></tr>
<tr><td colspan="4">Deliverable 6.1 – Conference paper, 6th SIDs contains numerical results of the COCTA project and an</td></tr>
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<tr><td colspan="4">overview of the COCTA project as a whole.</td></tr>
<tr><td>D6.2</td><td>Conference paper, 7th SIDs</td><td>11/12/2017</td><td>PU</td></tr>
<tr><td colspan="4">Deliverable 6.2 – Conference paper, 7th SIDs contains numerical results of the COCTA project and an overview of the COCTA project as a whole.</td></tr>
<tr><td>D6.3</td><td>Communication and dissemination report and data management update report</td><td>02/02/2018</td><td>PU</td></tr>
<tr><td colspan="4">This deliverable consists of two parts, the communication and dissemination report and the update of the data management report.
In the communication and dissemination report we provide a detailed overview of all communication and dissemination activities since the beginning of the project in April 2016. Major communication and dissemination activities include the project website, the project flyer, the distribution of news via mailing lists, one dedicated project workshop, scientific presentations and conference presentations, and the cooperation with the Advisory Board of the project. Future plans for communication and dissemination focus on the presentation and publication of the results of the final COCTA model, including an intensified communication to the general public.
In the update of the data management report we present capacity and demand related data that will be used for COCTA model testing and evaluation in the large-scale case study. We present detailed capacity data from eight ANSPs in Central and Western Europe, including a detailed analysis of airspace configuration in this area. Moreover, we discuss the data on airspace use which will be used for the modelling of the demand side in the large-scale case study.</td></tr>
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Table 9: Project Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

The COCTA concept of operations is very well aligned with the 'Trajectory-based operation' (TBO) concept outlined in the ATM Master Plan, since both focus on '*flight efficiency, predictability, environment and capacity, which becomes an important target*'. Although the TBO concept is of tactical nature, we see COCTA as a necessary extension of TBO over strategic and pre-tactical phase to achieve the final target of SESAR concept of operations 'Performance-based Operations' as '*European high-performance, network-centric, collaborative and seamless air/ground ATM system*'.

COCTA might also contribute to the vision of seamless ATM/C, which is addressed under 'Performance-based operations' in the ATM Master Plan. Moreover, the problem of uncoordinated ATM and ATC operations has been highlighted in the Network Manager Concept of Operations 2019: '*Network and ATC operation are currently not necessarily aligned, with network optimisation based on a planning that is not sufficiently accurate to allow execution fully in line with that planning. This results in reduced predictability for ATC and flight operations and inaccurate network measures (e.g. CTOT), negatively affecting trust in the system (over-deliveries, reduced declared capacity) impacting flight efficacy and delay figures.*' In our vision, COCTA is a potential initial step towards achieving such fluent-operating system in a redesigned ATM environment.

However, the COCTA concept is most related to demand-capacity balancing (DCB) and Airspace User Operations (AUO), as it proposes a new approach for capacity and demand management. Although COCTA does not go into operations details, it can be linked in general with several Operational Improvements and in the following table, we propose potential new enablers.

Code	Name	Project contribution	Maturity at project start	Maturity at project end
DCB-COCTA-01	*Coordinated Network-centric Dynamic Airspace Configurations*	*The COCTA project provides a concept and a mathematical model which jointly decides on configurations in the entire network, depending on anticipated traffic flows, to optimise total cost-efficiency.* *Presently, the COCTA concept is defined for strategic and pre-tactical level.*	*TRL0*	*TRL1*

Table 10: Project Maturity

3.2 Maturity Assessment

Table 11: ER Fund / AO Research Maturity Assessment

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Air Traffic Flow and Capacity Management (ATFCM) problem has been identified and elaborated. More specific problems have also been addressed: • Insufficient coordination in capacity provision on a network scale; • ANS capacity is not provided in line with demand; • Re-routings in the current system are not systematically coordinated at a network level Air Traffic Flow and Capacity Management (ATFCM) problem has identified and reported in D2.1 [1], and further elaborated in D5.3 [14]. Summary is also reported in this document (D1.2).
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Achieved	Several relevant aspects of the ATFCM problem have been identified and reported in D2.1 [1], D5.3 [14] and D1.2. For instance, the scope of ATFCM delay and estimated cost thereof, as well as costs of capacity, (under)utilisation of capacity, re-routing scenarios per year, etc.

TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Partial – Non Blocking	Some limitations of the current concept and modelling approach are reported in D5.1 [8], D5.2 [11] and D5.3 [14]. These limitations are almost exclusively related to the current scope of the research, which should be extended to tactical phase to be more realistically comparable to the current system (e.g. to take into account impact of the weather on capacity and operations).
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The whole concept and models are described in D5.3 [14]. More details about the concept can be found in D3.1 [5], D4.1 [6] and D4.2 [9].
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	COCTA research results, based on a large-scale case study in a part of the European airspace, for a whole day of operations, indicate that the proposed concept could bring: • tangible cost savings to airspace users, thus improving overall cost-efficiency, • managing same levels of traffic with less capacity, • but also significantly reducing delays and especially longer delays. These results are reported in the deliverable D5.3 [14].

TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	To summarize: • Innovations - ATM value-chain redesign, novel capacity and demand management concept, trajectory products and airport-pair charging. • Capabilities - coordinated capacity and demand management actions at strategic and pre-tactical level on a network level. • Obstacles - no major obstacles for technical implementation of the concept, but the concept should take into account some other SESAR solutions (based on discussion with the AB and stakeholders). Based on the results obtained, the COCTA concept looks very promising in delivering better network performance overall. Most notable, the COCTA concept and innovations it introduces enable the same level of traffic to be accommodated with less capacity in the network (thus reducing the cost to users) [14]. In discussion with stakeholders, we didn't find any major obstacles for technical implementation of the concept [12].
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Not Applicable	

TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Achieved	Considering the scope of the project for exploratory research, strengths and benefits have been clearly identified [14]: • Suitable concept and mathematical model for network performance optimisation under demand uncertainty, at different time levels, able to tackle large-scale instances in acceptable time. • Substantial cost-efficiency improvement resulting from network-wide, contract-based coordinated capacity and demand management. Some of the identified limitations are: • Current mathematical model (scalability, efficiency could be further improved, as indicated in D5.4), tactical phase and uncertainties not currently a part of the concept and a case study covering whole European airspace would be more representative. Immediate current and further research steps, based on the results, are defined and reported as an answer to question TRL – 1.11.

TRL-1.9	Have initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	COCTA related research has been published/reported in/at: • Journal papers: Transportation Research Part A: Policy and Practice [37]. One paper is currently under review in *Journal of Air Transport Management* and another in *Transportation Science*. • Conferences: SESAR Innovation Days [3], [4], [10], [44*]; World ATRS Conference [38]–[40]; Research Workshop on Volatility in Air Traffic and its impact on ATM Performance [13].
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved.	Research hypotheses can be found in several COCTA deliverables, the latest being in [14], in short: • COCTA concept improves cost-efficiency • COCTA brings better capacity allocation and utilisation in the network • COCTA concept reduces delays
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	The COCTA team has defined several immediate research actions and steps: • Sensitivity analysis of the results obtained (robustness of solution) • Enablers for more flexible capacity provision

			• Contractual options and relations between stakeholders Research steps for future are also defined: include tactical stage (ATM), real-time operations (ATC) and uncertainty in capacity provision taken into account in decision making. Based on recommendations from the Advisory Board and stakeholders, further research in this topic is both necessary and prominent [12].
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Partial – Non Blocking	COCTA project proposes a paradigm shift in the way capacity and demand are managed in the European ATM value-chain. Therefore, it is more operations/process-oriented innovation, rather than technology. The Advisory Board members and stakeholders showed great interest in the project concept and results and in how the project might proceed further. For instance, the novel approach to managing capacity and demand might be of interest to the NM, both to assess the impact on total cost efficiency and network performance and to further explore options for contractual relationships with ANSPs and AOs. Specific evidence of stakeholder support/interest include, among others, dedicated meeting/presentation to the NM director and his associates (Brussels, May 2018),

			meeting/presentation (upon invitation) to the Skyguide capacity management team (Geneva, July 2018), invitation for presentation at SESAR AU Solutions workshop, alongside exclusively higher maturity (IR) projects (expected Q4 2018), etc. Following upon stakeholder suggestions, an additional trajectory product has been incorporated into the concept ("premium trajectory" - PT). Preliminary and limited testing of thus-modified concept indicates that introduction of PT might negatively affect the cost-efficiency performance of the network as a whole (assuming, importantly, unchanged capacity order compared to previous setting with only two trajectory products). Further research of this matter is needed before reaching any definite conclusions and consequent policy implications in this regard. This includes, at the very least, investigation of AO preferences, delay costs and willingness to pay for the PT product under various circumstances, on one side, and of impact of such AO behaviour on the capacity ordering decision, on the other side.

4 Conclusion and Lessons Learned

4.1 Conclusions

The objective of COCTA is to propose and evaluate a redesigned Air Traffic Management environment in which the future Network Manager co-ordinately orders airspace capacity from ANSPs at strategic and pre-tactical levels, and offers different trajectory products at differentiated prices to Aircraft Operators, in such a manner to optimize overall network performance.

Based on the results of the large-scale case study with realistic data, we can conclude the following:

- COCTA improves total cost-efficiency, that is, cost of capacity provision and displacement cost, compared to a Baseline, which replicates the current system to the extent possible. Though persistent, this total cost-efficiency improvement varies, depending on traffic levels and traffic distribution in the network (~10% on average) [14].
- Cost of capacity is (pre)determined longer in advance (several months/years), i.e. at strategic and long(er)-term basis, and the COCTA concept demonstrates how to maximize the utilization of capacity ordered using trajectory products differentiation and pricing incentives (demand management) [14].
- Moreover, with demand management, the NM is able to steer AO trajectory choices to maintain a system optimum capacity-demand balance and network performance indicators from strategic stage [14].
- Compared to the Baseline scenario, COCTA is able to substantially reduce delay and especially longer delays (45+ minutes) as indicators of equity [14].
- This major delay savings comes at the expense of somewhat higher CO_2 emissions of a few additional kilograms per flight on average [14]. It should be noted, however, that this additional CO_2 emission is compared to shortest route, since the COCTA airport-pair charging does not send any incentive to fly longer routes (absent winds). Moreover, additional CO_2 can be traded-off with delays, should the policy maker set more rigorous environmental goals.
- In the present ATM system, re-routings are not considered in the capacity planning phase [21], but are executed in a form of mandatory (re-routing) scenarios on the day of operation to avoid excessive ATFM delays [41]. It is also worth noting that, in the present system, AOs are not always in favour of re-routings [42], not just because of the additional cost, but because there is no network-wide assessment of scenario impacts [43]. Namely, AOs are concerned that ANSPs use mandatory re-routing scenarios primarily as a tool to reduce ATFM delays to meet their local delay targets [42]. On the other hand, in the COCTA ATM value-chain, with airport pair pricing and trajectory charging introduced, re-routing becomes a network-centric instrument to effectively establish a demand-capacity balance, with clear benefits for AOs overall [14].

The COCTA project has introduced a novel approach to capacity and demand management in a re-designed ATM value-chain. The proposed approach to tackle the current challenges in ATM system offers clear benefits for stakeholders, based on a large-scale case study results.

4.2 Technical Lessons Learned

COCTA is not a technological project and therefore, there are no relevant technical lessons learned. However, we point out some of the challenges the research team faced during the project course.

One of the initial hypotheses was that the NM can provide sufficient incentives to AOs to reveal their trajectory preferences well in advance (weeks) to improve predictability for ANSPs and potentially reduce the cost of capacity provision. However, it is not easy to quantify and monetarise savings on the capacity side due to improved flights' (trajectory) predictability. After initial analysis [6] and extensive discussion with stakeholders, we concluded that it is not trivial to design a credible and reliable experiment to test the hypothesis, at least not in the current system, where capacity cost is largely fixed well in advance. After the meeting with the NM Director and his associates, in discussion with AO representatives, they suggested that one potential option for improving predictability would be to introduce an airport-pair and airspace corridor *reservation* in which a flight's trajectory will most likely be within. This essentially means reserving the right to fly between two airports in a certain portion of airspace at a designated time, which can be done several months in advance and should improve predictability for the NM. The NM could also apply a sort of two-part tariff: one part for reservation and one for the actual trajectory.

One of the most challenging aspects of the COCTA project was modelling, in particular developing an efficient model solution approach to deal with the problem complexity [14] and defining a sound AO trajectory product choice model [9]. The COCTA team has developed several solution approaches to tackle large-scale instances of the COCTA model, however, there is still room to improve them. Further work is also required on identification of realistic demand models. It is fair to say that we are currently making simple assumptions on choice behaviour, as well as on sequence of non-scheduled flights' appearance in the trajectory booking horizon that might significantly influence the results. Future work could look into using conjoint analysis or similar techniques to elicit AO's preferences and price sensitivities, which in turn would provide a more reliable basis for the demand model. Once defined in such a manner, it could also be of interest to dig deeper into ways of optimising decisions a bit more efficiently (quality versus time trade-off).

Related to modelling challenges are also data issues. While EUROCONTROL Demand Data Repository (DDR2) is suitable data source, in terms of data quality and quantity, for the general COCTA modelling, there is a data limitation for appropriate route-choice modelling. Namely, there is no data available to estimate a sound route-choice model. Only the last filed flight plan (FPL) data is available, and the FPL change log and/or initial flight plan are extremely time demanding to obtain. Therefore, it is not possible to track the evolution of a FPL, nor to relate the change in the FPL to an observable event (e.g. an AO re-routes a flight to avoid a long ATFM delay). Also, it is difficult to obtain a set of routes which were considered by an AO for a certain flight. This information might be available to flight dispatchers only and in discussion with AO representatives, they also agree that there are many variables to be considered to come up with a sound choice-model [9]. Moreover, they stressed that different AOs might have different preferences and that different AO experts will have different opinions, regarding trajectory choices in given circumstances.

4.3 Recommendations for future R&D activities (Next steps)

Some of the first steps which are within the focus of COCTA research which will refine and complement the current concept are:

- Sensitivity analysis of the results obtained. Namely, the COCTA team aims to explore several "what if" scenarios, for instance, to test the robustness of capacity decision if flights do not depart as planned. On the other side, we will evaluate how robust trajectory products are (especially margins) when capacity shortfall occurs in the network.
- Introducing enablers for a more efficient provision of capacity. The COCTA modelling is based on the existing airspace structure which is determined by the 'historic' boundaries of European ANSPs. Although this approach is suitable for a short to medium term perspective, the full potential of coordinated capacity provision and demand management cannot be exploited within this framework. Therefore, we will explore an additional scenario, assuming a flexible cross-border airspace configuration. A comparison between the original COCTA model (based on the existing airspace structure) and the COCTA model assuming a more flexible cross-border airspace configuration would help to identify the benefits of defragmentation within the European airspace.
- Contractual relationships between the stakeholders and the negotiation process. The COCTA team plans to explore what are the contractual options between the NM, ANSPs and AOs, as well as to further refine the negotiation process between them.

The concept of operations proposed in COCTA has a real perspective to enclose both tactical and real-time operations to wrap up a seamless Air Traffic Management/Control (ATM/C) concept package. Due to the complexity of the innovative idea and given the budget and timeframe, that endeavour is beyond the scope of this research and is planned as a part of future activities. These foreseen activities also take into account Advisory Board and stakeholders' recommendations.

Whereas we consider demand uncertainties in the COCTA concept and research carried out so far, we assume that the capacity will be provided as planned. This is a legitimate assumption, bearing in mind the horizon COCTA targets in demand-capacity balancing – strategic and pre-tactical phases, as well as the timeframe and scope of initially planned COCTA research. However, capacity is not necessarily delivered in the tactical phase as planned in the previous phases, due to ATM/C-internal reasons (Staffing, Capacity, Equipment, etc.) or due to external reasons (Weather, Military, etc.). To explicitly account for the tactical phase uncertainties on the capacity side, we need to re-define the COCTA mechanism and create a fundamentally different mathematical model, incorporating stochasticity. On the demand side, for instance, we could extend already developed models to take into account fair compensation should the level of service paid by the users cannot not be delivered.

One step ahead of tactical phase is real-time operations and ATM value-chain with seamless ANS provision. Within such system, there is a link between all stakeholders, similar to the currently developed ATM value-chain: the NM – AOs (AO Operation Centre and Aircraft) – ANSP communication and interaction in real-time. The decisions are made by all stakeholders in real-time in response to system dynamics and potential changes (e.g. weather, delays due to non-ATM/C reasons, etc.) that occur on a daily basis.

Based on a feedback received during the final COCTA workshop, stakeholders identified five areas that could be addressed in the future work. As a first step, the COCTA team should provide a more detailed elaboration of selected elements of the current COCTA concept. In particular, a more detailed description of the negotiation process between the Network Manager and the ANSPs was suggested (possibly including legal aspects). This suggestion is then linked to other suggestions, addressing specific issues which have to be governed by the contracts between the respective parties (long-term capacity investment and trajectory lifecycle, for instance). With a more elaborated COCTA concept, the COCTA team should address the tactical phase of operations, i.e. deviations from planned capacity provision and traffic forecasts. In particular, two of the most relevant questions to be answered are how the COCTA concept would work if (1) actual traffic deviates from planned traffic (e.g. caused by delays at a specific airport or due to weather conditions), and (2) what happens if less capacity is provided than it had been planned/agreed on. The latter point also refers to the contractual relation between the NM and the ANSP. To further enrich the COCTA concept, it should integrate additional elements of the air transport system, such as airport and terminal operations, to have a complete system (some stakeholders also mentioned an integration of military operations into the COCTA concept, and potentially unmanned aerial vehicle). Last, but not least, the COCTA concept should at least consider other SESAR solutions, such as Free Route Airspace or Flexible Use of Airspace, in order to increase the concept's level of maturity.

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Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition

Table 12: Glossary

A.2 Acronyms and Terminology

Term	Definition
AB	Advisory Board
ACC	Area Control Centre
ACE	ATM Cost-effectiveness
ANSP	Air Navigation Service Provider
AO	Aircraft Operator
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
COCTA	Coordinated capacity ordering and trajectory pricing for better-performing ATM
DCB	Demand-capacity balancing
DDR	Demand Data Repository
DT	Discounted Trajectory
EC	European Commission
FAT	Flexibly Assigned Trajectory
NEST	Network Strategic Tool
NOP	Network Operations Plan
O&D	Origin and destination
OR	Operational Research
PRC	Performance Review Commission

PST	Purchase Standard Trajectory
PT	Premium Trajectory
SES	Single European Sky
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SOSc	Sector-opening scheme
ST	Standard Trajectory
TRL	Technology Readiness Level

Table 13: Acronyms and technology

University of Belgrade
FACULTY OF TRANSPORT AND TRAFFIC ENGINEERING

WARWICK
THE UNIVERSITY OF WARWICK

Hochschule
Worms
University of Applied Sciences