Effects of capacity sharing on delays and re-routings in European ATM

Results of an ECAC-level simulation study

Jan-Rasmus Künnen,
Arne Strauss,
WHU Otto Beisheim School of Management,
Vallendar, Germany,
[arne.strauss; jan-rasmus.kuennen]@whu.edu

Nikola Ivanov,
Radosav Jovanović,
University of Belgrade – Faculty of Transport and Traffic Engineering, Belgrade, Serbia, [n.ivanov; r.jovanovic]@sf.bg.ac.rs

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

Marc Melgosa,
Universitat Politècnica de Catalunya,
Barcelona, Spain
marc.melgosa@upc.edu

Goran Pavlović,
EUROCONTROL,
Brussels, Belgium
goran.pavlovic@eurocontrol.int

***Abstract*—: In this paper we analyse the effects of capacity sharing between Area Control Centres on delays and re-routings. We assume two different design options for capacity sharing (within Air Navigation Service Providers and within Functional Airspace Blocks) and compare them to a baseline scenario. Using the CADENZA optimization and simulation model, we build a case study of a busy day in the ECAC area, using 100 different scenario runs in order to capture traffic variability as well as capacity reductions. Results show that capacity sharing leads to a decrease of delay and re-routing costs that outweighs the additional costs of enabling capacity sharing even if we assume relatively high additional costs per shared sector-hour. Moreover, it can be shown that capacity sharing within ANSPs already delivers ¾ of the benefits that can be achieved via capacity sharing within FABs.**

Network optimization, cross-border capacity sharing, delay, re-routing, cost

I. INTRODUCTION

Traffic variability and volatility, as well as capacity reductions due to e.g., staffing issues or weather, might lead to demand-capacity imbalances in some parts of the European network, causing disruptions and negatively affecting overall network performance. Overall, ATC capacity and staffing related reasons generated more than 2/3 of ATFM en-route delays in 2019 [1], with indications that this share could be even higher than reported [2].

One potential option for improving the performance of the network is the deployment of capacity-on-demand services [3], that is, a delegation of the provision of air traffic services to an alternate provider with spare capacity. There are already some examples for this type of capacity-sharing cooperation (e.g., FINEST [4]), but there are also several challenges associated with the implementation of the service, such as ATCO-licensing, charging etc. [5]. Therefore, it is important to understand the potential advantages of capacity-on-demand services across Europe [6] and, in particular, the effects of different scopes of geographical coverage and design options for such capacity sharing cooperation. In this paper we evaluate the impact on network performance of capacity sharing between Area Control Centres (ACCs) of the same Air Navigation Service Provider (ANSP) and capacity sharing across ANSP borders within the same Functional Airspace Blocks (FABs). The results of a large-scale study, covering almost the entire ECAC area with more than 30,000 flights for one day of operations, indicate the potential for cost savings for airspace users.

The remainder of this paper is structured as follows: Section II outlines the concept of capacity sharing and presents different design options. Section III presents the mathematical model for capacity sharing in European ATM. In Section IV, we discuss the results of capacity sharing on an ECAC-level simulation study and offer conclusions in Section V.

II. CAPACITY SHARING: CONCEPT AND DESIGN

Relatively low resilience in the European ATM, in particular in capacity provision, is to some extent due to the fact that *it relies on the provision of local ATM services for a defined geographical area* [3]. There are very limited options, if at all, to address local capacity shortages or issues by utilizing 'remote capacity services', and the usual approach is to delay flights or re-route them via airspace with spare capacity. One of the proposed solutions is capacity-on-demand service, as defined in the SJU Airspace Architecture Study, which *goes beyond the current static arrangements for cross-border delegation of ATS* [3].

A. General assumptions

In this paper we assume that adequate sector-independent (non-geographical) ATCO training and licensing procedures are in place, and that ATCOs are qualified/validated to handle traffic within airspace of a particular type (e.g. "sector-type validations" [7]). The ATCOs will carry out their operational duties and handle traffic from their regular working place, without the need for physical reallocation to another ACC/ANSP (i.e. 'virtual' capacity provision). We also assume that there are predefined 'alliances' between ACCs that agree on a reciprocal cross-licensing of some of their ATCOs.

All else equal, ATCO related costs in a system where ATCOs are licensed to handle traffic in other sectors, should be higher compared to the present system. Note that these costs are basically fixed costs for additional training, potential deployment of new support tools and system harmonization, as necessary. For the sake of this study, we however treat them as variable costs per sector hour, as one of the goals is to determine the optimum number of (sector-independent) licensed ATCOs. As there are currently no credible estimates, assumptions on additional licensing costs have to be taken and might be debatable. In the standard setting we assume that ATCOs with sector-independent license cost 10% more than the average of the ATCOs licensed for a sector group(s) in the alliance. We carry out sensitivity analysis which assumes a higher cost mark-up for sector-independent licensed ATCOs.

Our aim is to analyse capacity-on-demand service, that is, capacity sharing, as a 'hedge' against uncertainties in capacity provision and/or traffic flows. However, if the wage level within an alliance differs between the respective ANSPs, it might also be possible to 'outsource' services, i.e., substituting own 'expensive' ATCOs with cheaper ATCOs with sector-independent license from another ANSP. In order to avoid such incentives, we assume that the number of ATCO hours provided by each ACC in the capacity sharing settings must not be smaller than the number of ATCO hours in the baseline setting. This assumption prevents cross-border capacity sharing that is only motivated by different ATCO wage levels in different countries.

The benchmark for analysing the comparative performance of cross-border capacity provision is a situation without capacity sharing (we call this the 'baseline' setting), in which the capacity levels of each ACC (in terms of the number of ATCO hours to be provided) are taken from the levels reported by the ANSPs. The analysis is based on the CADENZA optimization model which is described in more detail in [11]. In short, the CADENZA model combines capacity and demand management in order to optimize network performance. For the pre-tactical and tactical phase, sector-opening schemes are determined and flights are assigned to trajectories in order to minimize total network cost, consisting of capacity provision cost and cost of delays and re-routings, resulting from lacking capacity. Within the framework of the analysis in this paper, we therefore already apply enhanced demand management measures in the baseline setting as well (to have a fair comparison between capacity management actions only), so that the cost performance is already superior to the one observed in European ATM today.

B. *Design options for alliances*

The idea behind cross-border capacity provision is to allow some flexibility in ATCO assignment between predefined pairs/groups of ACCs ('alliances'). There are several options for forming these pairs of ACCs, e.g. regional proximity, use of the same ATC system provider, or similarity of traffic patterns and associated complexity. In this paper we consider two different setups or alliances, covering different geographical scopes:

- *Capacity sharing at ANSP level (cross-ACC)*: sharing of resources among ACCs that are part of the same ANSP.
- *Capacity sharing at FAB level (cross-border)*: sharing of resources among ACCs that are part of the same functional airspace block (FAB), within the same ANSP as well as beyond ANSPs.

III. MATHEMATICAL MODELLING

The objective of capacity sharing is to improve the balancing of capacity with demand in the tactical phase of ATM, that is, to allow a more flexible adjustment of capacity levels (and thus sector opening schemes) in each ACC to manage upcoming traffic. By adjusting capacity to demand, capacity sharing should facilitate a routing of flights through the network that incurs lower delay and rerouting (i.e., displacement) cost. For the remainder of this section, we require the following notation.

Sets:	
$f \in \mathcal{F}$	Finite collection of flights
$r \in R^f$	Finite set of routes available to flight f
$u \in U$	Set of time periods
$a \in A$	Set of airspaces
$c \in C^a$	Set of configurations for airspace a
$l \in L^c$	Set of operating sectors corresponding to configuration c
$e \in E^l$	Subset of elementary sectors forming sector l
Parameters:	
$\kappa = (\kappa_l)$	Declared (nominal) sector capacity for each sector
$\bar{h} = (h_{ac})$	Sector-hours consumed by airspace a in configuration c
$k = (k_{acu})$	Capacity shortage in configuration c of airspace a at time unit u
$d = \left(d_r^f\right)$	Displacement cost of route r for flight f
$b = \left(b_{freu}\right)$	Indicates whether flight f on route r uses sector e at time u
$x = (x_a)$	Available capacity (in sector-hours) in airspace a
Decision variables:	
$\boldsymbol{x}^0 = (x_a^0)$	Capacity (in sector-hours) deployed in airspace a
$\boldsymbol{y} = \left(y_r^f\right)$	Indicates whether flight f is assigned to route r
$\boldsymbol{z} = (z_{acu})$	Indicates whether configuration c is open in airspace a at time u

A. *Standard setting without capacity sharing*

To determine the displacement costs incurred across all flights, given a certain distribution of capacities across ACCs, we need to jointly a) determine the sector opening scheme to be applied in each ACC given the available capacities (i.e., ATCO resources), and b) determine the most cost-efficient routing of flights in the network. Let *G(x,S)* represent the displacement (delay and re-routing) cost incurred from the most cost-efficient routing, given capacity vector *x* and traffic and capacity scenario *S*. Then we can determine *G(x,S)* with the following integer program:

$$\boldsymbol{G}(\boldsymbol{x},\boldsymbol{S}) = \min_{y,z} \sum_{f\in F^S} \sum_{r\in R^f} d_r^f y_r^f$$

$$\text{s.t.} \sum_{u\in U} \sum_{c\in C^a} \bar{h}_{ac} z_{acu} \leq x_a, \qquad a \in A \qquad (1)$$

$$\sum_{f\in F^S} \sum_{r\in R^f} \sum_{e\in E^l} b_{\text{freu}}\, y_r^f z_{acu} \leq \kappa_l, a \in A\ c \in C^a, l \in L^c, u \in U \quad (2)$$

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

$$\sum_{r\in R^f} y_r^f = 1, \qquad f \in F \qquad (4)$$

$$y_r^f \in \{0,1\}, \qquad f \in F, r \in R^f$$

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

The objective function minimizes the displacement cost across all flights. Constraint (1) ensures that the sector hours consumed by the sector opening schemes in each ACC do not exceed the ACC's available capacity; constraint (2) ensures that the routing of flights is feasible, i.e., the number of flights entering a sector does not exceed the capacity of that sector at any time. Constraint (3) ensures that one configuration is chosen for each ACC at each time period, and (4) ensures that one route is chosen for each flight.

Unfortunately, as shown in [14], the described integer program is *NP*-hard and therefore becomes computationally intractable even for medium-sized problem instances. In order to approximate a solution to the problem in polynomial time, we apply the two-step approach proposed in [11]: First, we determine the sector opening scheme for each airspace that will likely deliver the best network performance. Second, we determine the routing of each flight through the network such that the incurred displacement costs are minimized, given the capacity constraints determined by the fixed sector opening schemes.

For the first step, let k_{acu} represent the capacity shortage in airspace *a* at time period *u* given configuration *c*. We have $k_{\text{acu}} := \sum_{l\in L^c} \left(\sum_{e\in E^l} \sum_{f\in F^S} \sum_{r\in R^f} b_{freu} y_r^f - \kappa_l^S\right)^+$, where $x^+ := \max\{x, 0\}$ and routing decision y_r^f is determined by assigning all flights to their shortest trajectory. Note that k_{acu} depends on scenario *S* such that the sector opening scheme is adjusted to each scenario. The sector-opening scheme is then decided by solving the configuration integer linear program (CILP):

$$\min_{z} \sum_{a,c,u} k_{acu}\, z_{acu}$$

$$\text{s.t.} \sum_{u\in U} \sum_{c\in C^a} \bar{h}_{ac} z_{acu} \leq x_a, \qquad a \in A \qquad (1)$$

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

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

In the second step, we can then determine the feasible routing of flights using the MMKP-based heuristic summarized in Algorithm 1 below and described in detail in [11].

Algorithm 1 MMKP-based heuristic for routing problem

```
    Input: Configuration $C'$, traffic scenario $F^S$ and capacity uncertainty $W^S$
1: Initialize: Set $r_f' := argmin_{r\in R^f} d_r^f$ for $f \in F^S$, Lagrange Multiplier $\mu_l := 0$ for $l \in L'$
2: Establish feasible solution: Iterate until $\bar{k}_l \leq 1 \forall\, l \in L'$
3:        Compute relative "weight" $w_{frl} = \sum_{e\in E^l} b_{freu}/k_l^S$ for $f \in F^S, r \in R^f, l \in L'$
4:        Compute relative capacity shortage $\bar{k}_l = \sum_{f\in F^S} w_{fr'l}$ and set $l^* := argmax_l \bar{k}_l$
5:        For flights with $w_{fr'l^*} > w_{frl^*}$ on $l^*$, store $\gamma_r^f = \frac{d_r^f - d_{r'}^f - \sum_{l\in L'} \mu_l (w_{fr'l} - w_{frl})}{w_{fr'l^*} - w_{frl^*}}$ for $r \in R^f$
6:        Determine flight and route with lowest $\gamma_r^f$, update $r_f' = r$ and $\mu_{alu^*} = \mu_{alu^*} + \gamma_r^f$
7: Improve feasible solution: Iterate until no further improvement found, i.e., $\Delta d = \emptyset$
8:        For flights and routes with $d_{r'}^f > d_r^f$ and $\bar{k}_l - w_{fr'l} + w_{frl} \leq 1$ store $\Delta_r d = d_{r'}^f - d_r^f$
9:        Find flight and route with largest $\Delta_r d$ and update $r_f' := r$
    Output: Routing $R^* = \{r_f' : f \in F^S\}$ and displacement cost $D^* = \sum_{r\in R^*} d_r$
```

We initialize the procedure by assigning each flight $f \in F^S$ to the route with lowest displacement costs. Let $L' = \{l \in L^{c'} : c' \in C'\}$ be the sectors defined by C'. To establish a feasible solution, we then iteratively reassign flights on the most congested sector l^* until all sectors $l \in L'$ are within capacity limits κ_l^S (which depend on W^S). If we set w_{frl} to be a relative "weight" of a flight f with route r on sector l, then we can calculate a relative capacity shortage $\bar{k}_l$. To decide which flight to reassign to another route, we first determine flights and routes which decrease capacity overload in the most congested sector l^* (i.e. flights and routes with a positive value $w_{fr'l^*} - w_{frl^*}$).

Then we compute a decision parameter γ_r^f that weighs the change in displacement costs with the change in overload in the most congested sector. Finally, we test if we can use potential spare capacities to further improve this feasible solution. For that purpose, any flight f and route r is reassigned from current route

r' to r, if this reassignment improves displacement costs while keeping the routing feasible.

With this two-step procedure developed for the standard setting without capacity sharing, we can approximate the displacement costs incurred in the network for any capacity budget *x* and scenario (of traffic and capacity uncertainties) *S*. In the following, we adjust the procedure to incorporate the additional flexibility provided by capacity sharing into the model.

B. *Modelling shared capacities*

Within the presented modelling framework, the value of capacity sharing lies in the ability to more flexibly adjust the sector opening scheme of an ACC based on the materialized traffic and capacities given in each scenario *S*. More technically, rather than being constrained by the capacity level x_a of each ACC in constraint (1), we may instead operate a more resource-intensive configuration in one ACC and a less resource-intensive configuration in another ACC so long as the total resource consumption across all ACCs of an alliance is not exceeded.

Let *G* be the set of all alliances across the network (indexed by *g*), let A_g be the set of ACCs that are part of alliance *g*, and let x_a^0 be the capacity (in sector hours) consumed by ACC a. We can then determine displacement cost *G(x,S)* from the most cost-efficient routing (including capacity sharing) as follows:

$$\begin{array}{lll}
\boldsymbol{G}(\boldsymbol{x},\boldsymbol{S}) = \min\limits_{y,z} \sum\limits_{f\in F^S} \sum\limits_{r\in R^f} d_r^f y_r^f & & \\
\text{s.t. } (2), (3), (4) & & \\
\sum\limits_{a\in A_g} x_a^0 \le \sum\limits_{a\in A_g} x_a, & g\in G & (5)\\
\sum\limits_{u\in U} \sum\limits_{c\in C^a} \bar{h}_{ac} z_{acu} \le x_a^0, & a\in A & (6)\\
x_a^0 \in \mathbb{N}^+, & a\in A & \\
y_r^f \in \{0,1\}, & f\in F, r\in R^f & \\
z_{acu} \in \{0,1\}, & a\in A, c\in C^a, u\in U. &
\end{array}$$

Again, since solving the integer program to determine *G(x,S)* exactly is computationally intractable, we resort to the two-step approach presented above. In order to incorporate the additional level flexibility provided by capacity sharing in selecting sector opening schemes for each ACC, we adjust the CILP accordingly:

$$\begin{array}{lll}
\min\limits_{h^0,z} \sum\limits_{a,c,u} k_{acu}\, z_{acu} & & \\
\text{s.t.} \sum\limits_{u\in U} \sum\limits_{c\in C^a} \bar{h}_{ac} z_{acu} \le x_a^0, \;\; a\in A & & (5)\\
\sum\limits_{a\in A_g} x_a^0 \le \sum\limits_{a\in A_g} x_a\,, & g\in G & (6)\\
\sum\limits_{c\in C^a} z_{acu} = 1, & a\in A, u\in U & (3)\\
x_a^0 \in \mathbb{N}^+, & a\in A. &
\end{array}$$

IV. RESULTS

To analyse the impact on network performance of capacity sharing, we test the proposed capacity sharing settings against the baseline without capacity sharing on a large-scale case study covering almost the entire ECAC area (Figure 1). We first present the case study used for the analysis and then discuss results on all settings.

A. *Case Study*

We apply the developed optimization approach to a large-scale case study, which we defined based on one of the busiest days in 2018 (7th September). We use Eurocontrol DDR and R&D Archive services to retrieve demand and capacity data. On the capacity side we include 118 ACCs/sector groups across 40 ANSPs in the ECAC area including upper, lower and several terminal airspaces. We use declared sector (or associated traffic volume) capacities, as well as active sets of sector configurations for each respective ACC/sector group. On the demand side, we use the last-filed flight plans of almost all flights crossing the airspace and generate shortest plannable trajectories using DYNAMO tool [15]. We do not include flights which have the same departure/arrival airport, helicopter flights and flights operated by military aircraft, for instance.

In order to take into account the significant level of uncertainty on the capacity as well as on the demand side, we use a large number of scenarios. On the capacity side, the different scenarios cover reductions, either by lowering declared capacity of sectors (e.g. due to weather) or lower staffing levels (staffing issues); the assumed likelihood of these events in different regions is based on historical observations. On the demand side, we combine scheduled traffic (as observed in reality) with a random selection of non-scheduled flights, taken from a pool of actual flights in the respective airspace.

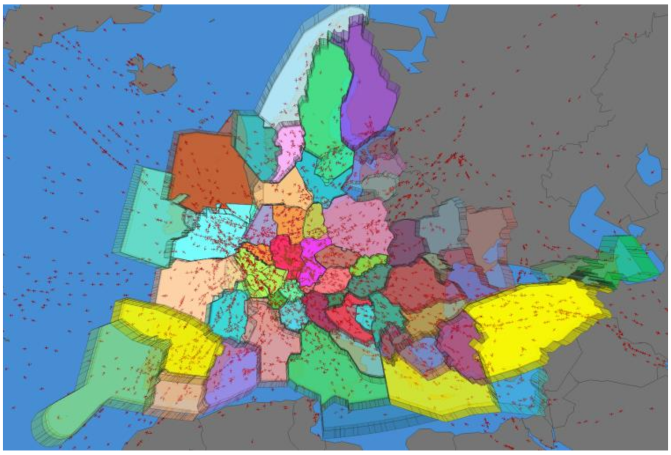

Figure 1. Scope of ECAC-level case study, including snapshot of flights.

Within our simulation approach we analyse total (variable) cost, in particular the cost of capacity provision (based on ATCO cost per sector-hour) and the cost of capacity shortage, causing delays and re-routings. Variable costs of capacity provision are defined as average ATCO costs as reported in [8]. We estimate per aircraft delay costs based on [1] while re-routing costs are calculated directly in DYNAMO based on additional flying time and fuel burned.

B. *Evaluation methodology*

To test the different design options for capacity sharing, we apply the methodology proposed in section III to both capacity sharing settings. For *cross-ACC sharing*, we define each ANSP as a separate alliance in $g \in G$, with each alliance containing all ACCs that are part of the respective ANSP. For *cross-border sharing*, we define each FAB as a separate alliance, which consists of all ACCs that are part of the respective FAB. We compare the performance of both design options with the baseline setting (without capacity sharing) on 100 testing scenarios. Each scenario reflects a different materialization of traffic volume, weather and ATCO availability across the network. Recall that the value of capacity sharing lies in flexible adjusting capacities to these uncertainties.

C. *Numerical results*

In this section, we present the effect of capacity sharing on network performance in our case study. Performance is measured in terms of the variable capacity, delay and rerouting cost incurred in each setting as well as the variation of delay and rerouting cost across the analysed scenarios. We also conduct a sensitivity analysis to assess how robust our results are to changes in the cost markup for capacity sharing.

1) *Network performance*

Table I reports the cost performance across the three settings. Even though the capacity costs under capacity sharing are slightly higher than without capacity sharing (due to the 10% cost markup), the savings in displacement cost make up for the increase. Overall, total variable network cost can thus be reduced by 110,980 EUR (-1.9%) and 156,885 EUR (-2.7%) for the cross-ACC and cross-border sharing models, respectively. In particular, the sizable saving under cross-ACC sharing indicates that capacity sharing within ANSPs is already sufficient for generating large benefits. Moreover, the variation in network cost is reduced in both settings for capacity sharing, showing that flexibility reduces the impact of large distortions in the network.

TABLE I. VARIABLE COST OF CAPACITY AND DISPLACEMENT COSTS

Setting	Capacity cost	Displ. cost	Network (total) cost	Cost savings
Baseline	5,012,019	757,205	5,769,224±81,438	
Cross-ACC	5,027,930	630,314	5,658,244±70,375	-110,980 (-1.9%)
Cross-border	5,026,039	586,300	5,612,339±66,516	-156,885 (-2.7%)

All costs in EUR

2) *Required levels of capacity sharing*

Eventually, the feasibility of capacity sharing (whether within or across ANSPs) will depend on the extent of such sharing required across airspaces. Table II compares the number of resources employed locally and virtually (i.e., for capacity sharing) between the settings. We find that in order to reap the benefits from capacity sharing, only 595-720 sector-hours (or 2-3%) of flexible capacity were required in the simulation. In practice, this implies that in most cases it is sufficient to have one ATCO pair available in each ACC that is able to operate across ACCs (i.e., to change flexibly between ACCs to manage traffic).

It is important to note that this estimate is a minimum requirement for one (busy) day of operations only. The actual number of ATCOs that would need to be trained to make such a "hedge" available during prolonged period of time would, inter alia, depend on rostering and other working time arrangements. Furthermore, the amount of sector hours provided virtually would have to be somewhat higher and adequately balanced between ACCs, in order to maintain ATCO validation/competence and required safety levels. In practice, that would imply a coordinated rostering approach with flexible distribution of "virtual" sector hours between ACCs, even in periods when sharing is not actually driven by operational needs (e.g. traffic shifts and/or capacity shortages).

TABLE II. CAPACITY LEVELS FOR ALL SETTINGS

Setting	Local	Virtual
Baseline	22,097	-
Cross-ACC	21,337	720
Cross-border	21,502	595

Measured in sector-hours

3) *Displacement cost variation*

As shown in Table I, capacity sharing effectively reduces the average displacement cost across all 100 testing scenarios. In Figure 2, we show how different settings perform in each of the analysed 100 scenarios, where the variability in demand and disruptions in capacity provision (and thus the incurred displacement cost) increase from left to right. tential in displacement cost across the network.

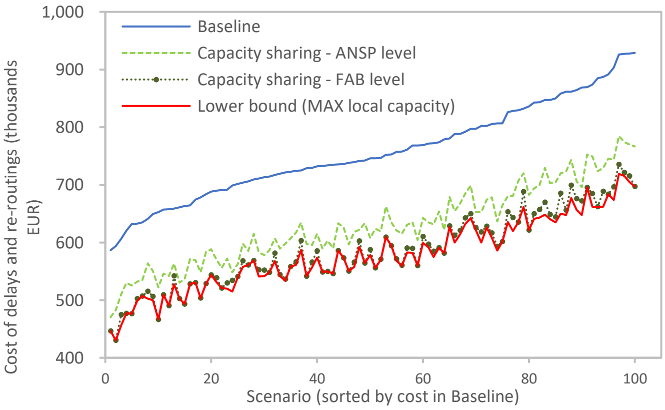

Figure 2. Displacement cost variation across all scenarios (n=100)

We find that with capacity sharing we can reliably reduce displacement cost in each of the 100 scenarios, leading to a more stable network performance. This way, airspace users will benefit from more reliable schedules for their daily operations. We also compare the performance of the three settings against a 'lower bound', which we model by using the maximum number of sector hours that was reported during the summer period 2018 in each ACC. The comparison shows that the displacement costs observed under cross-border sharing (and with a small gap also the costs under cross-ACC sharing) are very close to this lower bound in all 100 scenarios. Therefore, in our simulation study, cross-border sharing (with only 595 sector hours provided *virtually)* realizes almost the full savings po

4) *Displacement cost over time*

In order to better understand under which conditions capacity sharing proves beneficial, we also analyse the displacement cost of all three settings over time. As shown in Figure 3, we find that the benefit of capacity sharing (measured as the difference between displacement cost with and without capacity sharing) is largest in the morning and afternoon/evening peak periods (note that we do not have information on aircraft/crew/passengers' connections, so these are not explicitly accounted for, but indirectly through inclusion of reactionary cost of delay). Some alternative approaches to capacity sharing have analysed the effect of 'merging' airspace sectors at times of low demand in order to reduce redundancies in capacity provision; these analyses have unsurprisingly found the benefit of such 'merging' to be largest in the off-peak periods (e.g., at night). However, we use capacity sharing in our study predominantly as a means to hedge against displacement cost uncertainty, and thus not as a means to reduce capacity redundancies.

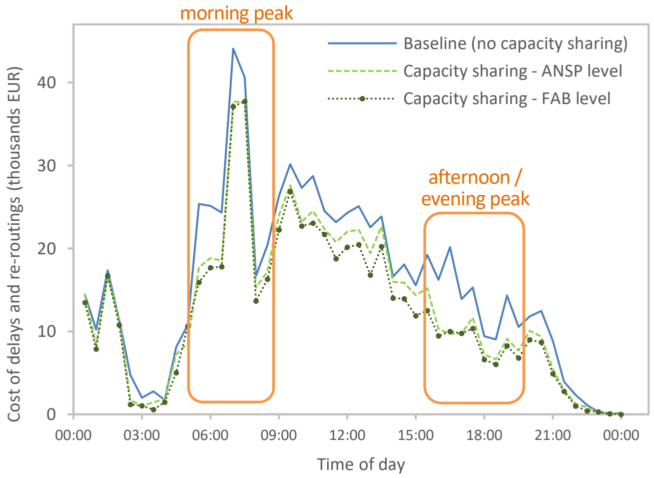

Figure 3. Average displacement costs incurred by departure time.

5) *Sensitivity to cost*

In order to implement capacity sharing in European airspace, the additional costs of enabling such flexibility play a crucial role – next to legal and practical restrictions. Since the (monetary) benefits of capacity sharing decrease with increasing cost of enabling such flexibility, we analyse in Table III the sensitivity of the reported savings to changes in the cost markup (for virtually-provided sector hours). As shown, the savings from cross-ACC sharing decrease from 1.9% to only 0.5% if a cost markup of 50% (instead of 10%) is assumed. In comparison, the savings potential for cross-border sharing decreases from 2.7% to 1.5% for the same change in cost markups, and is therefore slightly less sensitive to the variable cost of capacity sharing.

TABLE III. SENSITIVITY OF CAPACITY SHARING MODELS TO COST

Setting	Capacity cost	Displ. cost	Network (total) cost	Cost saving
Baseline	5,012,019	757,205	5,769,224	
Cross-ACC (10% markup)	5,027,930	630,314	5,658,244	-110,980 (-1.9%)
Cross-ACC (25% markup)	5,067,707	630,314	5,698,021	-71,203 (-1.2%)
Cross-ACC (50% markup)	5,107,484	630,314	5,737,798	-31,426 (-0.5%)
Cross-border (10% markup)	5,026,039	586,300	5,612,339	-156,885 (-2.7%)
Cross-border (25% markup)	5,061,089	586,300	5,647,389	-121,835 (-2.1%)
Cross-border (50% markup)	5,096,138	586,300	5,682,438	-86,785 (-1.5%)

All costs in EUR

The reason for the observed difference in sensitivities is that cross-border sharing requires fewer virtual sector hours than cross-ACC sharing to realize the savings potential. It is worth noting, however, that in practice the cost markup for capacity sharing within the same ANSP (i.e., for cross-ACC sharing) is likely to be lower than the cost markup required for capacity sharing across ANSPs (i.e., for cross-border sharing).

D. *Limitations*

The case study presented in this paper is based on a very busy day in the European airspace. One might argue that for less busy periods there might be smaller gains of cross-border capacity provision, as there are lower displacement costs in the local setting. On the other hand, there is still some probability of unexpected capacity shortages (e.g., short-notice ATCO shortages due to medical reasons). Whereas in the baseline setting each ACC would have to provide its own capacity buffer (e.g., ATCOs on 'standby'), costs for such buffers would be reduced in the cross-ACC and cross-border settings even in periods of low traffic. This effect is not covered by the current CADENZA model which only analyses the number of sector hours and not the number of ATCOs needed to provide these sector hours. Consequently, the CADENZA model would have to be supplemented by an ATCO rostering model (which is currently in progress, see [12]) and some assumptions on capacity buffers within each ACC. It is worth noting that certain capacity buffers during the day of operations might arise from the ATCO shift design itself, i.e. inability to perfectly match ATCOs with expected demand profile due to rostering rigidity. Cross-border capacity sharing could open the possibility of utilizing such buffers that would otherwise remain geographically locked.

Another aspect that is worth considering concerns potential reductions in declared sector capacities due to higher ATCO workload caused by unfamiliar operational environment. This would limit the extent of benefits from cross-border sharing to a certain degree. Research is ongoing [7] to come up with mitigation measures for such issues by identifying additional information needs, enhancing decision support tools etc. As mentioned in section IV-c, balanced distribution of virtually provided sector hours is also expected to serve as a mitigation measure for such capacity reductions.

V. CONCLUSIONS

In this paper we summarize the results from applying the CADENZA simulation model to decisions on cross-border capacity provision. For a case study representing a busy day in the almost entire ECAC area we show that large benefits can be generated by introducing flexibility with regards to capacity sharing into the network, in which only a small share of ATCOs is required to control aircraft also in sectors that belong to a partner ACC. The rationale is quite simple: if an unexpected shift in traffic leads to overcapacity in one ACC and a lack of capacity in some other ACC, ATCOs that are not needed in one ACC might provide services in the other ACC. Consequently, delays and re-routings (implying additional fuel consumption) can be avoided.

In the model presented in this paper, cross-border capacity provision reduces distortions in the network caused by traffic volatility, which implies some reciprocity between ACCs within an alliance. Even in cases of a longer lasting traffic shift, e.g., caused by military conflicts, cross-border capacity provision might be beneficial. In the case that this longer lasting shift leads to unidirectional cross-border capacity provision, ANSPs would have to negotiate on compensation payments for service provision. However, if the entire European airspace is simultaneously affected by a large disruption leading either to a boost in traffic or a huge crisis (like in the case of the COVID-19-pandemic), cross-border capacity provision cannot solve the resulting issues.

ACKNOWLEDGMENT

This project has received funding from the SESAR Joint Undertaking within the framework of SESAR 2020 and the EU's Horizon 2020 research and innovation programme under the Grant Agreement Number 893380.

REFERENCES

[1] EUROCONTROL PRC (2020). “An Assessment of Air Traffic Management in Europe during the Calendar Year 2019 – Performance Review Report”.

[2] EUROCONTROL PRC (2020). “Technical note on en-route capacity. A perspective on all aspects of en-route capacity”.

[3] Single European Sky ATM Research 3 Joint Undertaking. (2019). A proposal for the future architecture of the European airspace. Publications Office. https://doi.org/doi/10.2829/309090.

[4] EANS (2019). FINEST. https://www.eans.ee/en/tegevused/arendustegevused/finest. Accessed on 1st October 2022.

[5] European Commission (2020). “Legal, economic, and regulatory aspects of ATM data services provision and capacity on demand as part of the future European air space architecture”. Final Report.

[6] N. Solčianska, A. Gasparin, L. Castelli, T. Bolić (2021). “Capacity sharing within Virtual Centre: How much delay can be reduced?”. 11th SESAR Innovation Days.

[7] SESAR JU (2020). PJ10 PROSA (Controller tools and team organisation for the provision of separation in air traffic management). Final Project Report.

[8] EUROCONTROL (2020). “ATM Cost-Effectiveness (ACE) Report 2018”.

[9] Ivanov, N., Jovanović, R., Fichert, F., Strauss, A., Starita, S., Babić, O., & Pavlović, G. (2019). Coordinated capacity and demand management in a redesigned Air Traffic Management value-chain. Journal of Air Transport Management, 75, 139–152. https://doi.org/10.1016/j.jairtraman.2018.12.007.

[10] Künnen, J.-R., & Strauss, A. K. (2022). The value of flexible flight-to-route assignments in pre-tactical air traffic management. Transportation Research Part B: Methodological, 160, 76–96. https://doi.org/https://doi.org/10.1016/j.trb.2022.04.004.

[11] J.-R. Künnen, A. Strauss, F. Fichert, N. Ivanov, R. Jovanović, and S. Starita (2022). Cross-border capacity planning in air traffic management under uncertainty. *Working paper, WHU - Otto Beisheim School of Management*.

[12] G. Pavlović, R. Jovanović, M. Stanojević (2022). Rostering practices and ATCO productivity in Area Control Centres: how much spare capacity is there and how to make best use of it? 10th International Conference on Research in Air Transportation (ICRAT), Tampa, Florida, USA.

[13] S. Starita, A.K. Strauss, R. Jovanović, N. Ivanov, and F. Fichert (2016). Maximizing ATM cost-efficiency by flexible provision of airspace capacity. 6th SESAR Innovation Days, Delft, the Netherlands, 8-10 November.

[14] Starita, S., Strauss, A. K., Fei, X., Jovanović, R., Ivanov, N., Pavlović, G., & Fichert, F. (2020). Air Traffic Control Capacity Planning Under Demand and Capacity Provision Uncertainty. Transportation Science, trsc.2019.0962. https://doi.org/10.1287/trsc.2019.0962.

[15] Dalmau Codina, R., Melgosa Farrés, M., Vilardaga García-Cascón, S., & Prats Menéndez, X. (2018). A Fast and Flexible Aircraft Trajectory Predictor and Optimiser for ATM Research Applications. ICRAT 2018-8th International Conference for Research in Air Transportation, Castelldefels, Espanya, 26-29 Juny 2018 (pp. 1-8).