

Enhancing Dynamic Airspace Configuration and Flight-Centric ATC through Clusterized Aircraft Early Handover

Toward a Cooperative Capacity-on-Demand Framework in Air Traffic Management

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Abstract—Clusterized early handover (CAEHO) is an innovative capacity-on-demand technique in Air Traffic Management (ATM) that mitigates sector overload by delegating the control of selected aircraft to adjacent sectors with available spare capacity, reducing reliance on costly and disruptive Short-Term ATFCM Measures (STAM). The CAEHO concept has been previously proposed and demonstrated its potential for targeted delegation. Building on this foundation, two new variants are introduced: fixed-area delegation and composable-area delegation. Taking advantage of the CAEHO framework, these variants can be interpreted as enhanced forms of Dynamic Airspace Configuration (DAC) and Flight-Centric ATC (FCA), respectively, extending their applicability with early delegation principles. All three mechanisms are described and comparatively assessed in terms of operational principles, procedural integration, and suitability within the framework of Letters of Agreement (LoA). The analysis identifies distinct advantages, limitations, and implementation requirements for each variant, offering practical insights for their integration into current operations. The results provide a structured basis for developing flexible early handover solutions to support capacity-on-demand strategies in overloaded sectors.

Keywords—Clusterized aircraft early handover (CAEHO), Fixed-area handover, Composable-area handover, ATC-capacity regulations, Capacity-on-demand

I. INTRODUCTION

Air Traffic Management (ATM) encompasses the integrated management of airspace and aircraft movements, with the objective of ensuring safety, operational efficiency, and cost-effectiveness [1]. This coordination involves a seamless interaction between airborne and ground-based systems, facilitated by a broad set of stakeholders including airspace users, Air Navigation Service Providers (ANSPs), and the Network Manager. Despite the progress achieved in recent years through improved coordination and advanced planning techniques, ATM continues to face a central challenge in the ECAC area: limited airspace capacity, particularly in sectors experiencing high traffic demand.

A primary response to these limitations has been the implementation of Short-Term Air Traffic Flow and Capacity Management Measures (STAM), such as ground delays, flight level

capping and horizontal re-routings [2], which aim to address demand–capacity imbalances during the day of operations. These measures have been progressively refined under the Integrated Network Management and ATC Planning (INAP) framework [3], spanning the pre-tactical window from six hours to fifteen minutes before operations. Within this framework, the Demand–Capacity Balancing (DCB) service plays a pivotal role by aligning sector capacities with expected traffic loads, and adapting the airspace configuration accordingly.

Nevertheless, usual approaches to DCB often rely on re-configuring the airspace by splitting or activating additional sectors when discrepancies between planned and actual demand exceed manageable thresholds. While this practice can temporarily mitigate sector overload, it may still result in some sectors becoming congested while adjacent ones remain under-used [4]. The inherent rigidity of sector geometry boundaries could be identified as a fundamental limitation of the current system, as it prevents the airspace from adapting at the same rate as the rapidly evolving traffic dynamics. To address this gap, new operational paradigms were introduced, most notably Dynamic Airspace Configuration (DAC) [5] and Flight-Centric ATC (FCA) [6], both aiming to overcome the structural constraints imposed by fixed sectorization and to provide more flexible capacity management.

DAC provides a flexible approach by reshaping sector boundaries according to evolving conditions, using methods to balance workload and improve capacity [7]. FCA, in turn, proposes a more disruptive shift: abandoning sector boundaries altogether and assigning controllers to flights rather than to portions of airspace [8].

Finally, an innovative early delegation mechanism of control responsibilities provides a capacity-on-demand strategy with significant potential. The Clusterized Aircraft Early Handover (CAEHO) mechanism [9] exemplifies this approach by alleviating sector overload through the early transfer of control for selected aircraft to adjacent sectors with spare capacity, before the aircraft reach the exit waypoint of the congested area. Rather than modifying flight trajectories or imposing ground



delays, CAEHO adjusts the system's effective capacity by redistributing sectors occupancy count among adjacent sectors. The mechanism identifies clusters of eligible aircraft, based on spatial proximity, heading, and remaining dwell time, and coordinates their early handover to downstream sectors, delegating control and communications to the receiving sector's ATCo team. This proactive task load redistribution reduces the reliance on STAM measures and resectorization, and may significantly reduce the deployment of ground regulations by absorbing excess demand at sector level, thereby enhancing operational flexibility. The CAEHO operationalizes the concept by transferring aircraft to sectors with available capacity, thereby allowing controllers with lower demand improving their cost-efficiency (CEF2 [10]) and reducing occupancy count on overloaded sectors.

A detailed analysis was carried out to assess this dependency, confirming that the mechanism's feasibility hinges on identifying and exploiting underused capacity in real time. It has been stated in some contexts that DAC refers to spare capacity but does not explicitly model it. [7]. In contrast, the concept of sector spare capacity is not applicable to FCA, since its sectorless architecture does not operate on the basis of geographic sector boundaries.

This distinction suggests that the triggering logic of CAEHO, which is based on detecting occupancy imbalances within a defined time frame where overload in one sector coincides with spare capacity in adjacent sectors, can provide a concrete operational criterion for DAC and guide adaptations in FCA. In a similar FCA-based approach, this could take the form of dynamically composing temporary, capacity-driven elementary spatial units of airspace, effectively creating short-lived structures assigned to controllers. Aircraft could be clusterized into perishable ecosystems shaped by their spatio-temporal interdependencies, with these transient ecosystems defining the composable areas delegated to controllers, adapting their shape to the position of the selected clusterized aircraft, and dissolving when the last selected aircraft leaves the sector. More broadly, it is the explicit consideration of spare capacity in adjacent sectors that establishes a common foundation for CAEHO, DAC-based, and FCA-based adaptations, thereby enhancing their practical viability as capacity-on-demand mechanisms.

This paper examines three early delegation modalities for mitigating sector overload: cluster-based delegation (CAEHO), fixed-area delegation, and composable-area delegation. These approaches differ in whether aircraft, entire airspace volumes, or modular spatial units are transferred, and each involves distinct comparative analysis of flexibility, coordination, and compatibility with existing Letters of Agreement (LoA).

1. Cluster-based delegation. The first modality, *Clusterized Aircraft Early Handover* (CAEHO), consists of dynamically transferring control of groups of aircraft that are spatially and temporally aligned. Clusters are selected according to shared heading, conflict-free status, remaining dwell time, and destination sector, ensuring that only traffic directly relevant for balancing is delegated. The ANTICIPATE project, funded

under the SESAR 3 Joint Undertaking, is developing and testing this concept. Preliminary results indicate its potential to improve sector balancing, reduce ground regulations, and increase ATM system agility [9].

2. Fixed-area delegation. The second modality consists of delegating control over entire predefined areas, such as standard airblocks or geographical volumes defined in Letters of Agreement (LoAs). This strategy does not depend on the positions or behavior of individual aircraft. It can offer procedural and operational advantages due to its alignment with existing coordination frameworks, reduced traffic flow dependence, and clearer legal boundaries. However, it lacks the granularity and adaptiveness of cluster-based or composable-area approaches, which may limit effectiveness in highly dynamic or asymmetric traffic scenarios.

3. Composable-area delegation (Flexible areas). The third modality shifts the delegation focus from aircraft to dynamically perishable Areas of Responsibility (AoRs). Rather than transferring entire fixed airblocks, this approach involves the delegation of small, predefined responsibility units (minimal spatial cells or elementary spatial units) that can be transferred individually or combined. These units act as building blocks of a flexible delegated area that can be tailored to match traffic patterns or overload geometries. The activation of these elementary spatial units is linked to the presence of specific aircraft, and as traffic streams evolve, the delegated area adapts accordingly: new elementary spatial units can be switched on while others are switched off, until the sector progressively returns to its original shape. While this method requires procedural support to enable convex modular delegation, it offers a compromise between the aircraft-level precision of CAEHO and the procedural simplicity of fixed-area delegation.

The comparative insights gained from this study provide a practical foundation for selecting and tailoring early delegation mechanisms to specific operational contexts. By clarifying the procedural pathways and identifying potential integration challenges, the results support informed decision-making by both operational stakeholders and regulatory bodies. This perspective also offers a basis for future simulation campaigns and field validations aimed at refining capacity-on-demand solutions and ensuring their seamless incorporation into the broader ATFCM framework.

II. EARLY DELEGATION STRATEGIES: CLUSTERIZED, FIXED-AREA, AND COMPOSABLE-AREA MODALITIES

This section presents the operational foundations and defining features of the three early delegation modalities analyzed in this study. While all share the common goal of preemptively offloading traffic from overloaded sectors, they differ in what is delegated, aircraft, fixed spatial regions, or modular AoRs, and in how this delegation is executed in practice.

The objective of this section is to clarify the operational principles behind each modality and to highlight their respective trade-offs in terms of flexibility, procedural complexity, coordination requirements, and regulatory compatibility.



To illustrate the practical implications, advantages, and limitations of each delegation modality, a representative use case was selected. The sector EDUUKI1C at 09:23:00 on 27/07/2024 (see Figure 1) serves as the reference scenario. At that moment, the sector was subject to an ATC-capacity regulation and was forecast to exceed its maximum declared capacity at the tactical phase, making it a suitable candidate for testing early delegation mechanisms under operational stress. This case study offers a concrete basis for visualizing the performance of each modality in a real-world situation involving sector congestion and heightened coordination requirements.

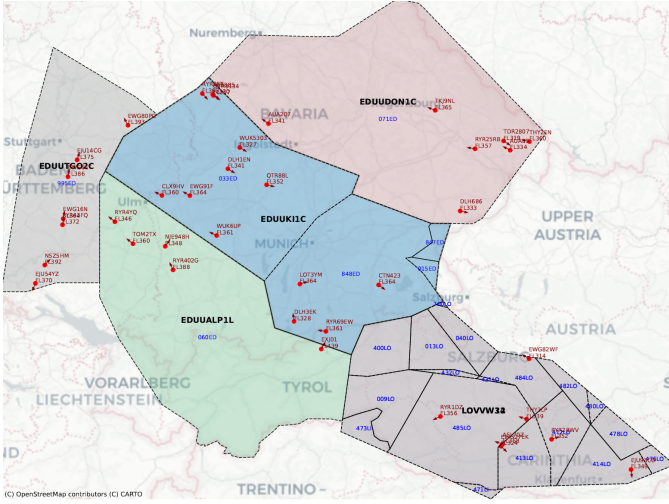


Figure 1. EDUUKI1C sector and its adjacent active sectors at 09:23 on 27 July 2024, including observed traffic

In reference to Figure 1, the sectors considered in this analysis are EDUUKI1C, represented in blue at the center and composed of two airblocks (033ED and 848ED); EDUUTGO2C, depicted in gray to the west with a single airblock (995ED); and EDUUALP1L, shown in green to the south and also consisting of one airblock (060ED).

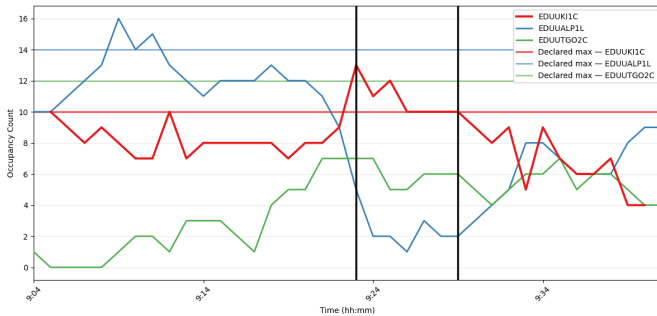


Figure 2. EDUUKI1C, EDUUTGO2C, and EDUUALP1L sectors occupancy count at 09:23 on 27 July 2024

Figure 2 illustrates the core rationale for applying early handover mechanisms, namely the relationship between occupancy counts and available spare capacity across sectors. The solid red line represents the occupancy of EDUUKI1C, which reached 13 at 09:23, exceeding its declared capacity of

10 (shown by the horizontal orange line), and thereby triggered an ATC-capacity regulation. In contrast, the occupancy of EDUUTGO2C was 7 (solid green line), five below its declared capacity of 12 (green horizontal line), while EDUUALP1L registered an occupancy of 5 (solid blue line), nine below its declared capacity of 14 (gray horizontal line). It can be observed that, during this period, the EDUUKI1C sector remains at or above its declared capacity for more than six minutes (from 09:23 to 09:29), while the adjacent sectors exhibit substantially lower occupancy levels, remaining well below their respective declared capacities over a comparable timespan. This situation illustrates a favorable case for early handover, as the occupancy imbalance allows delegating control to balance sector loads without altering traffic flows.

Although there are several metrics to estimate the sector capacity [11], according to Eurocontrol's validation results in PJ08 AAM25 [12], and the metrics calculated by NEST [13], the dynamic evolution of the occupancy count effectively reflects potential ATCO overloads. This supports its use in the present analysis as a reliable and operationally meaningful indicator for assessing sector capacity and traffic regulation needs.

A. CAEHO mechanism

The CAEHO mechanism enables proactive transfer of control and communications for selected en-route aircraft by identifying and delegating clusters of eligible flights to adjacent sectors with spare capacity before boundary crossing.

To ensure operational feasibility and safety, multiple eligibility criteria must be satisfied. Only conflict-free aircraft are considered, with potential conflicts resolved in advance. Eligibility is further constrained by the remaining dwell time within the overloaded sector: candidate aircraft must have more than one minute but less than seven minutes remaining. Flights outside this time window are either handed over normally (if too close to the boundary) or excluded (if too far), due to increased uncertainty and coordination complexity.

CAEHO is strictly limited to en-route operations above FL240. Delegation is performed at the aircraft cluster level, not for individual flights, to improve coordination efficiency and ensure operational impact. All adjacent sectors involved must be active, and flight levels must be compatible at the time of transfer.

At its core, CAEHO clusters aircraft by remaining dwell time while ensuring compliance with constraints on direction, en-route status, flight level, adjacency, conflict freeness, and downstream impact, producing coherent groups that can be safely transferred to adjacent sectors. This mechanism mitigates sector overload, enables flexible and targeted delegation, optimizes airspace utilization, reduces reliance on disruptive capacity regulations, and supports data-driven decision making with scalability across different traffic conditions.

Preliminary results from the ongoing project indicate that CAEHO can be activated within the operational phase, potentially up to two minutes before the predicted onset of an overload episode. This suggests that CAEHO enables near

real-time action without prior structural reconfiguration, allowing the redistribution of workload among controllers before congestion occurs.

Using planned ECAC traffic from AIRAC cycle 2407 [14], several sectors were identified in which the occupancy count exceeded the declared capacity. Internal analyses show that up to 97% of these exceedances could have been avoided by transferring the control and communications of eligible flights to adjacent sectors with available spare capacity, verified at the exact moment of exceedance and throughout the overload episode. These findings demonstrate CAEHO's potential as an operational mechanism for real-time traffic redistribution when adequate spare capacity and coordination conditions are present, although broader quantitative assessment remains ongoing.

Additionally, more than 98% of predicted overload episodes lasted less than ten minutes, indicating a promising window of opportunities for CAEHO in short-lived congestion events.

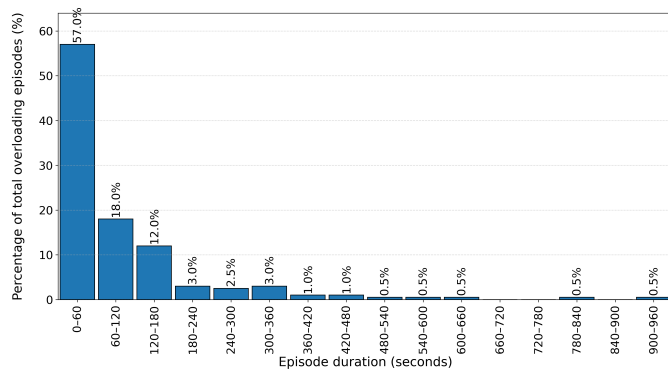


Figure 3. Duration of overloading episodes

While Figure 3 showed the distribution of exceedance peaks by duration, Figure 4 details their internal composition. Each duration bin is subdivided by exceedance magnitude, expressed as the number of aircraft above the declared capacity, with sub-bars showing the percentage of peaks in each category. Shorter peaks are mostly associated with lower magnitudes, which is consistent with the fact that large exceedances rarely vanish within a short time window.

In this use case, Figure 5 illustrates a set of aircraft eligible for early handover to the EDUUTGO2C sector, while maintaining their planned trajectories. CLX9HV, EWG91F, and WUK6UP (circled in green) meet the required conditions for early handover, sufficient remaining dwell time, conflict-free trajectories, and compliance with delegation criteria. Only the control of these aircraft is delegated, while the responsibility for providing air traffic control service within the sector remains with the original controller (ATCo 1). In this situation, the transferred aircraft fall under the tactical control of ATCo 2, whereas ATCo 1 continues to ensure separation for the remaining traffic within the sector. To avoid inconsistencies, a coordinated or shared-responsibility framework is required, since both controllers may temporarily operate within the same airspace portion when CAEHO is applied.

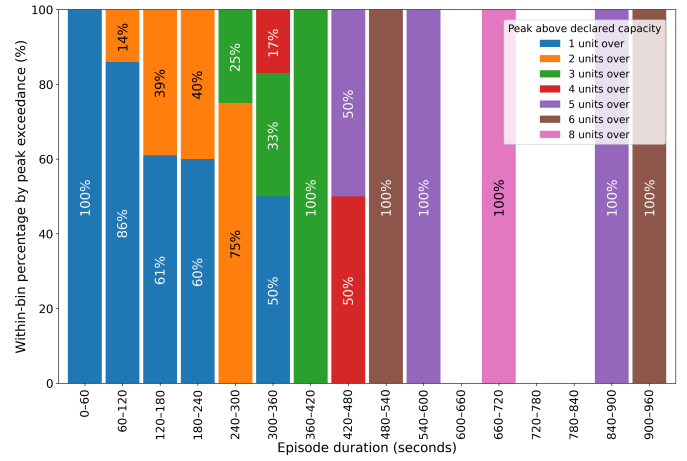


Figure 4. Percentage distribution of exceedance peaks by duration, with each bin subdivided by exceedance magnitude (number of aircraft above declared capacity)

In line with solutions proposed in Flight Centric ATC [15], this framework can be supported by decision-aid tools that identify the aircraft best suited to resolve a conflict, together with conflict detection and resolution functions that explicitly assign resolution responsibility to one controller [16].

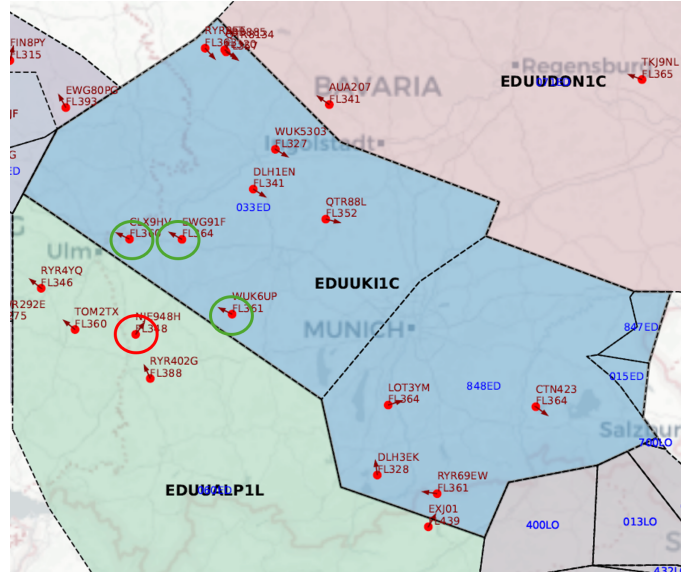


Figure 5. Aircraft eligible for early delegation of control (circled in green).

Advantages and Limitations of the CAEHO Approach

The CAEHO mechanism offers several operational benefits but also poses notable challenges. Below is a structured overview of its main advantages and limitations.

• Advantages

- 1) *High flexibility in delegation.* The mechanism allows transferring a targeted number of selected aircraft without risking overload in receiving sectors, as clusters can be distributed across multiple adjacent sectors based on spare capacity.

- 2) *Fixed delegation set.* The number of delegated aircraft is known and bounded at the moment CAEHO is triggered. Since no area is involved, additional aircraft cannot enter the delegation scope later.
- 3) *Balanced workload distribution.* By selecting specific aircraft clusters for delegation, workload can be actively and proportionally redistributed between sectors.
- 4) *Minimal impact on sector geometry.* As no airspace volume is delegated, sector boundaries remain unchanged.
- 5) *Short-term applicability.* CAEHO is particularly suitable for short-lasting overload episodes.
- 6) *Pre-entry accommodation.* Receiving ATCos can accommodate the delegated traffic a few minutes ahead of its physical entry at the waypoints, providing temporal flexibility for overload mitigation.

• Limitations

- 1) *Multiple controllers.* Although control of selected aircraft is transferred, the overloaded sector controller remains responsible for the area, so coordination with the receiving controller may be needed if a conflict arises.
- 2) *High sensitivity to conflict-freeness.* Many candidate aircraft may be excluded if conflicts are detected, especially in dense or intersecting traffic flows.
- 3) *Strict dwell time constraints.* Eligibility is highly dependent on sector dwell time; aircraft outside the narrow window cannot be delegated.
- 4) *Coordination complexity.* On 27 July 2024, and according to preliminary tests, only 34% of exceedances could be resolved by delegating to a single adjacent sector, indicating that broader applicability requires multi-sector delegation and synchronization of the CAEHO mechanism.
- 5) *Limited adaptability to dynamic traffic.* Once clusters are selected, the system is less responsive to evolving traffic patterns.
- 6) *Increased procedural load.* Both ATCo 1 and ATCo 2 must follow clearly defined roles within a shared airspace (similar to FCA), which may introduce procedural overhead and cognitive burden.

B. Fixed-Area Delegation

As an alternative to cluster-based delegation, the *Fixed-Area* approach transfers control responsibilities over a single, pre-defined and geographically anchored airspace volume rather than over individual aircraft. The delegated region is selected from airblocks, and is activated as a whole when required, without re-shaping.

Unlike CAEHO, where only selected aircraft are transferred, in fixed-area delegation both the control and the responsibility over the pre-defined region are handed over to the receiving controller (ATCo 2). Within the active area, ATCo 2 holds full operational authority to manage separation, conflicts, and maneuvers for all aircraft present.

Symmetrically, ATCo 1 is fully relieved of responsibility within the activated region and does not need to monitor or manage the behavior of aircraft inside that area, including traffic entering from other directions (e.g. NJE948H). This method simplifies coordination and Letters of Agreement at the cost of one size fits all shortages.

If certain spatial and operational conditions are met, such as geometric suitability and available spare capacity in an adjacent sector, applying CAEHO to a fixed area may result in a DAC-like action. However, the underlying logic remains different. CAEHO is driven by the expected behavior of the occupancy count only minutes before the overload, which minimizes uncertainty and enables immediate action. While DAC is planned within the INAP timeframe [3], CAEHO acts much closer to the moment of imbalance and responds directly to the detected exceedance. Even when a DAC-like configuration could emerge, CAEHO would still focus on exploiting nearby spare capacity indicated by occupancy dynamics. Although DAC may become more time sensitive [3], it would continue to account for broader factors such as complexity and workload, among others, whereas CAEHO would provide a more direct operational reaction.

Figure 6 shows how the 033ED airblock is intended to be transferred to the EDUUTGO2C sector; however, since the number of aircraft whose control is transferred depends on the volume of the delegated airspace, in this case 9 aircraft would be transferred from EDUUKI1C and 7 were already present in EDUUTGO2C, resulting in a total of 16 aircraft, which is 4 above the declared capacity of 12. Therefore, the early delegation of this area to EDUUTGO2C is not feasible.

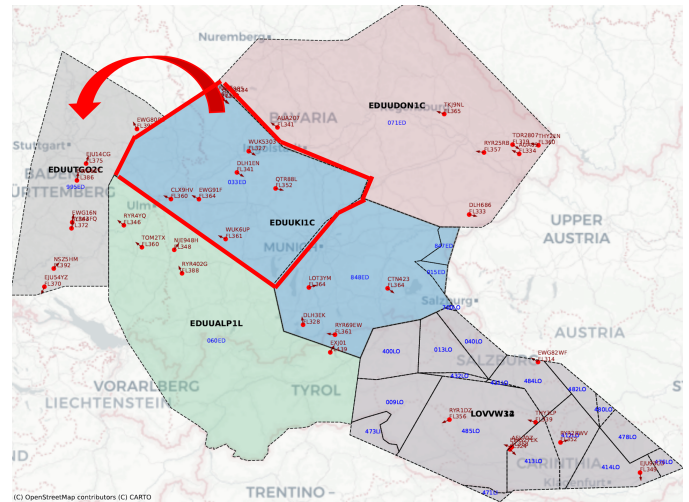


Figure 6. Fixed-area (airblock) transfer not feasible due to low spare capacity

While the notion of a downstream sector was meaningful within the CAEHO methodology, where headings and trajectories were used to select eligible candidates, this concept loses its sense in the airblock-based approach, as several aircraft within the same airblock may follow different headings. Consequently, the delegated airblock can be transferred to

any sector that is adjacent to it, regardless of its relative position. In this case, the transfer of the 033ED airblock to the EDUUTGO2C sector would be feasible, as this sector has a spare capacity of 9 and could accommodate the 9 aircraft delegated from the airblock (see Figure 7).

Although the performance of the fixed-area mechanism has not been directly assessed, internal results in Section II-A show that only 34% of the regulations could be solved by delegating a single cluster. This limitation is likely even greater for fixed-area delegation, since it is less selective and usually involves transferring the control of additional flights, which reduces flexibility and effectiveness.

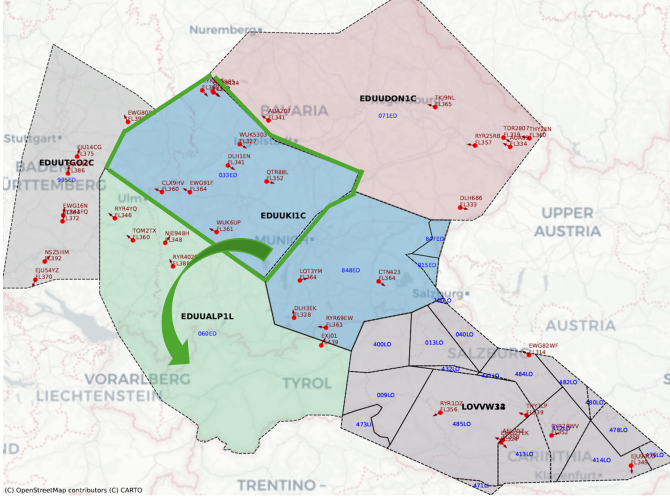


Figure 7. Fixed-area (airblock) transfer feasible due to enough spare capacity

Advantages and Limitations of the Fixed-Area Delegation Approach

• Advantages

- 1) *Procedural simplicity.* A single, pre-defined region is activated as a unit, which simplifies coordination and reduces on-the-fly geometry decisions.
- 2) *Full responsibility transfer.* The receiving controller (ATCo 2) assumes complete responsibility within the activated area, clarifying roles and handover points.
- 3) *Predictable boundaries.* Published shapes and transfer points are stable over time, which eases training and supports standard operating procedures.
- 4) *Straightforward inclusion in LoAs.* A limited catalog of pre-defined regions can be incorporated in Letters of Agreement with clear activation criteria and constraints.

• Limitations

- 1) *Tyranny of geometry.* Fixed shapes may not align with moving clusters or dominant flows, potentially capturing irrelevant aircraft or missing relevant ones.
- 2) *Potential inefficiency.* Although the overload can be mitigated, some divergencies may appear: one

sector may remain under its nominal conditions (e.g., EDUUK11C), while the receiving sector may operate closer to its capacity limits (e.g., EDUUALP1L).

- 3) *Edge effects and dwell time.* If the area is narrow or poorly placed, short transits near the boundary can increase handovers and coordination.
- 4) *Over-delegation.* As the entire area is delegated, all aircraft inside are transferred, which may exceed the receiving sector's spare capacity and limit the mechanism's flexibility.
- 5) *Back-transfer risk.* An aircraft that has already left sector A and entered sector B may be temporarily transferred back to sector A if it is located within a delegated area. This situation can create a "ping-pong" effect, which may appear unnatural as the aircraft is delegated back and forth between sectors.
- 6) *Switching-off constraints.* Returning an area to its original sector requires that sufficient spare capacity is available in the receiving sector, and the switching-off procedure may be delayed until the declared limits are respected.

C. Composable-Area Delegation

A new methodology is proposed that integrates the main features of CAEHO (aircraft clusters), DAC (dDCB), and FCA (ATCos assigned to aircraft clusters), while also drawing on principles of Dynamic Airspace Sectorization (DAS) [17]. First, a fitted area is constructed around the flights selected (i.e., aircraft clusters) for early delegation, following the cluster-based approach of CAEHO. This area is then formalized as a transferable unit, in line with the principles of DAS, where structures follow flows rather than flows follow structures, enabling a spatially coherent delegation. Unlike the other proposed methods, the composable area is always convex and contained within the boundaries of the overloaded sector: it modifies the internal structure of the sector without trespassing its limits. Finally, the delegated area dynamically follows the trajectories of the selected aircraft, consistent with the FCA concept, and progressively shrinks as each delegated aircraft exits the sector. The process concludes once the last selected aircraft has left the sector, ensuring that the delegated volume adapts continuously to the operational situation.

Figures 8 illustrate the basis of the composable-area configuration: first, the area is fitted around the selected candidate aircraft (Figure 8a); second, the area dynamically follows their trajectories (Figure 8b); and finally, the area vanishes once the last selected aircraft leaves the sector (Figure 8c).

The control of the airspace volume has been delegated to the EDUUALP1L sector, since the notion of a downstream sector is missing, and the traffic patterns and flows near the boundary make this delegation feasible, thereby easing the tasks of the receiving ATCo.

A grid of square cells, each measuring 10.8 NM per side, has been implemented in this study and uniquely identified, enabling the dynamic composition of airspace volumes in

wrapping techniques [25], where h is the number of vertices on the hull. In this work, the convex hull is computed using the Quickhull algorithm, for its robustness and efficiency with two-dimensional point sets of moderate size.

This study focuses on two-dimensional hulls, since the delegation problem is lateral within sector boundaries. As direct computation of $CH(P)$ from elementary areas may extend beyond sector limits, the hull is intersected with the sector polygon S :

$$CH_S(P) = CH(P) \cap S \quad (2)$$

Ensuring that the delegated area remains entirely within the original sector boundaries.

Advantages and Limitations of the Composable-Area Delegation Approach

• Advantages

- 1) *Full responsibility transfer.* The receiving controller (ATCo 2) assumes complete responsibility for the delegated area, simplifying coordination and reducing ambiguity.
- 2) *Improved procedural clarity.* ATCo 1 is fully relieved of any monitoring duties for the delegated region, reducing cognitive and operational workload.
- 3) *Targeted yet structured flexibility.* Modular elements shape the delegated region to evolving traffic, combining CAEHO's precision with fixed-area simplicity while avoiding unnecessary airspace delegation.
- 4) *Determinism.* Given the same set of input points, the algorithm produces a unique polygon, supporting reproducibility and coordination between units.
- 5) *Adaptability.* As the positions of eligible aircraft change in real time, the convex hull can be recomputed rapidly, enabling dynamic reconfiguration of the delegated area.

• Limitations

- 1) *Inclusion of non-target aircraft.* Although less likely than in fixed-area delegation, the selected composable-area may still encompass aircraft not intended for transfer.
- 2) *Increased procedural complexity.* All possible area combinations must be predefined and approved in the LoA, increasing administrative burden.
- 3) *Dependence on predefined elements.* Flexibility is constrained to the set of pre-approved units, and increasing the granularity of these units for greater accuracy can significantly complicate operational procedures.
- 4) *Real-time assembly requirement.* The appropriate combination of modular units must be selected dynamically during operations.
- 5) *Spatial awareness sensitivity.* Frequent changes to the delegated configuration can complicate controllers' spatial awareness compared to static fixed-

area delegation, as the shape and boundaries of responsibility shift more often.

- 6) *Composable-area release.* In composable-area delegation, areas disconnect progressively rather than abruptly. Nevertheless, release remains subject to the spare capacity of the sector regaining control, which must be within limits before the transition is completed.
- 7) *Implementation status.* This method remains in an early stage and is not yet supported by a validated toolchain for efficiency assessment, validation, or operational integration.

III. THE ROLE OF THE LETTER OF AGREEMENT

The transfer of control and communication between air traffic control units is governed by ICAO Annex 11 (*Air Traffic Services*) [26] and ICAO Doc 4444 (*Air Traffic Management*) [27]. These establish the principles for coordination, the responsibilities of adjacent units, and the conditions for formal handover, providing the legal and operational foundation for regional agreements.

In Europe, delegation provisions are formalized through the EUROCONTROL Common Format Letter of Agreement (LoA) [28], which standardizes jurisdictional limits, transfer rules, and coordination procedures between adjacent ATS units in line with ICAO requirements.

This framework is directly relevant to early handover. Fixed-area delegation aligns most naturally with existing LoAs, though it lacks flexibility. Clusterized CAEHO is more effective operationally but diverges from current structures, creating procedural challenges. Composable-area delegation offers a balanced compromise, using reconfigurable yet predefined geometries to combine adaptability with regulatory consistency.

As LoAs already provide the recognized instrument for defining inter-unit coordination, early handover could be integrated within this framework without additional legal structures. Its provisions on responsibilities, transfer conditions, and mutual amendments offer a transparent basis for formalizing early delegation in line with existing regulations.

IV. CONCLUSIONS AND FUTURE WORK

This study examined three early handover variants, clusterized delegation (CAEHO), fixed-area delegation, and composable-area delegation, as capacity-on-demand measures to mitigate ATC-capacity regulations by transferring the control of flights to adjacent sectors with spare capacity.

Each variant presents a trade-off between flexibility, performance, and ease of application within existing procedures. Clusterized CAEHO enables precise targeting of overload drivers but requires conflict-free aircraft and accurate selection. Fixed-area delegation integrates easily into existing Letters of Agreement (LoA) but suffers from rigidity and the risk of transferring surplus traffic. Composable-area delegation offers intermediate flexibility by combining predefined spatial elements, though it raises spatial awareness demands if configurations change frequently.

Under realistic demand, clusterized CAEHO is most effective, fixed-area delegation underperforms due to inflexibility, and composable-area delegation shows promise for balancing adaptability and safety, if supporting tools are available. Procedurally, all variants can be framed within the LoA structure: fixed-area aligns most naturally, CAEHO requires tailored arrangements, and composable-area demands adaptations yet may remain compatible, though not in a straightforward manner.

Future research will address AI-based clustering for CAEHO, benchmarking of fixed-area delegation, and flexible geometries for the composable-area concept. ANTICIPATE will extend current assessments through fast-time simulations to quantify these mechanisms, considering ATCo procedures using a Socio-Technical Simulation Model.

ACKNOWLEDGMENT

This work has received funding from the SESAR Joint Undertaking under the European Union Horizon Europe research and innovation programme (Grant Agreement No. 101166947, ANTICIPATE) and from Grant PK620616 PID2023-150782OB-C21, funded by MICIU/AEI/10.13039/501100011033.

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