



Assessing stakeholder impacts of capacity regulations and algorithmic capacity-on-demand mechanisms in European air traffic management: A network-level ECAC operational case study

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ABSTRACT

Regulatory mechanisms in European air traffic management, including Air Traffic Flow Management slot allocation and flow restrictions, are widely used to address sector-level demand-capacity imbalances. Although effective for safety and feasibility, they impose departure delays that propagate through airline rotations, increasing costs, reducing passenger reliability, and disrupting airport operations. Standard Air Traffic Flow and Capacity Management assessments mainly report regulation compliance and aggregate delay, without explicitly assessing network propagation or differentiated stakeholder impacts.

This paper compares the regulatory baseline with an algorithmic demand-capacity balancing approach based on early delegation of clusters of aircraft to adjacent sectors. Under congestion, control of eligible aircraft is proactively reassigned to reshape sector occupancy profiles and balance workload across neighboring sectors, without changing traffic demand or declared capacities.

A stakeholder-oriented framework evaluates impacts on airlines, passengers, airports, and air navigation service providers, combining monetized indicators with proxy metrics where valuation is not feasible. Results indicate that early delegation substantially reduces the need for sector-level Air Traffic Controller capacity regulations, lowering direct and reactionary delay and associated costs. Reduced delay propagation is associated with more stable schedules and a smoother temporal distribution of demand for airport infrastructure and services.

Overall, rigid regulation-driven allocation can create system-level inefficiencies even when safety constraints are satisfied. Adaptive, data-driven balancing mechanisms show potential to improve efficiency and to alter the distribution of congestion-related impacts, informing policy discussions on the evolution of demand-capacity management in European air traffic systems.

1. Introduction

Air transport systems are subject to multiple regulatory interventions that shape how airlines schedule and operate their services. While these regulations are intended to ensure safety, fairness, and capacity discipline, they may unintentionally generate inefficiencies in the temporal allocation of flights. For example, Air Traffic Flow Management (ATFCM) departure slots, curfews, and other

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flow- and capacity-management restrictions can introduce artificial delays in departure or arrival schedules. Once introduced, such delays tend to propagate across the daily program, creating knock-on effects for airlines, airports, and passengers (Cook et al., 2004).

These propagated delays impose costs well beyond immediate disruption. Airlines face higher operating costs from fuel burn, crew reallocation, and disrupted rotations, while passengers experience longer travel times and reduced reliability. Airports and ground handlers face congestion peaks that strain terminal and ramp capacity. Although these multi-actor consequences are acknowledged in policy debates, systematic frameworks to quantify and compare them remain scarce. In other transport modes, stakeholder-oriented evaluation approaches have been developed - for example, the European Investment Bank's RAILPAG framework (European Investment Bank (EIB), 2005) - but their application to aviation delay management remains limited.

In road transport, congestion has been mitigated by adaptive control mechanisms such as ramp metering, which regulates motorway entry to balance demand and capacity (Mizuta et al., 2014). An analogous logic can also be explored in ATM, although the parallel is conceptual rather than operational: unlike road ramp metering, the relevant mechanisms do not stop or slow aircraft, but use flexibility in capacity provision in time and/or space to reduce demand-capacity imbalances.

In Air Traffic Management (ATM), several capacity-on-demand concepts aim to respond to demand-capacity imbalances by increasing operational flexibility. Some approaches, such as Dynamic Airspace Configuration (DAC) (Eurocontrol, 2023) and Dynamic Airspace Sectorization (DAS) (Xu et al., 2024), achieve this by dynamically reshaping sector boundaries or regrouping airspace elements in order to redistribute workload. Other approaches, including Flight-Centric ATC (FCA) (Melgosa et al., 2020) and early-delegation mechanisms, seek to redistribute control responsibilities without modifying the underlying sector geometry.

Within this latter category, the Clusterized Aircraft Early Handover (CAEHO) (Borràs et al., 2024; Borràs et al., 2025) mechanism enables the early delegation of aircraft control and communications from overloaded sectors to adjacent ones, thereby redistributing controller task load while preserving the published sector configuration.

Within the European ATM framework, Airspace Management (ASM) and Air Traffic Flow and Capacity Management (ATFCM) address complementary layers of system performance: ASM shapes the structural configuration and deployment of airspace resources (EUROCONTROL, 2017), while ATFCM manages demand-capacity imbalances across strategic, pre-tactical and operational phases (EUROCONTROL, 2023b).

CAEHO is compatible with both governance layers. Within ASM, it does not alter sector boundaries but may enhance the effective flexibility of existing configurations by intensifying controlled interactions between adjacent sectors, potentially reducing the need for additional sector openings (Borràs et al., 2024). Within ATFCM, it offers a localized sector-to-sector demand-capacity balancing mechanism that can complement traditional regulation measures without redefining the structural configuration (Borràs et al., 2025).

The CAEHO mechanism was originally introduced and operationally analyzed in prior work, where emphasis was placed on controller workload redistribution, sector-level feasibility conditions, and tactical implementation constraints (Borràs et al., 2025; Borràs et al., 2024, 2026). Within that body of research, CAEHO was examined as a capacity-on-demand instrument embedded in ASM-ATFCM interactions.

Building on this operational foundation, the present paper shifts the analytical perspective from feasibility and workload redistribution to system-level economic implications. Specifically, it investigates the stakeholder-level effects of deploying such adaptive flexibility as a substitute for selected ATFCM regulatory measures. Regulatory delay is therefore used here as an observable and quantifiable benchmark for assessing inefficiencies in demand-capacity balancing, without implying that regulation avoidance fully characterises the broader contribution of CAEHO within the ATM architecture.

However, the policy relevance of such mechanisms cannot be established solely on operational metrics. For transport regulators and network managers, the central question concerns whether adaptive sector balancing reduces aggregate delay costs, how these benefits are distributed across airlines, passengers, airports, and Air Navigation Service Providers (ANSPs), and whether such redistribution aligns with institutional and incentive structures. These economic and distributional dimensions have not been systematically addressed in prior CAEHO-oriented studies.

The central research question addressed in this paper is whether adaptive sector-level demand-capacity balancing can deliver measurable and distributable economic benefits relative to selected ATFCM regulatory interventions.

This paper contributes to the literature in three main ways.

First, it develops a stakeholder-oriented analytical framework to evaluate the economic implications of replacing selected ATFCM regulatory interventions that are operationally avoidable through adaptive sector balancing with a CAEHO-based demand-capacity management strategy. Rather than focusing on controller workload redistribution, the framework quantifies monetized delay reductions for airlines and passengers and assesses airport and ANSP implications through non-monetised operational proxy indicators.

Second, using a simulation model that contrasts observed regulatory practice with a counterfactual adaptive allocation strategy, the study provides a consistent comparison of delay propagation, cost exposure, and distributional effects across stakeholder groups. This shifts the analytical perspective from sector-level operational feasibility to system-level economic performance.

Third, by linking aviation flow management with established insights from adaptive congestion control in surface transport, the paper situates air traffic regulation within the broader transport economics literature, highlighting institutional trade-offs, efficiency gains, and potential incentive misalignments associated with more flexible demand-capacity balancing mechanisms in the European ATM system.

2. Literature review

Research on air-traffic management (ATM) regulation has long recognized that rule-based mechanisms governing access to scarce capacity-particularly airport slots and flow-management regulations-shape not only airport-level performance but also the

dynamics of delay propagation across the network (Cook et al., 2004; Martin and Socorro, 2009). Early work on system bottlenecks and queues already pointed to the structural consequences of allocating demand to constrained resources without adaptive feedback, where congestion shocks inflate tactical delays and generate cumulative knock-on effects throughout downstream sectors (Cook et al., 2004). Subsequent empirical and regulatory analyses confirmed that, in the European context, the interaction between declared airport capacities, ATFCM regulations and rigid slot-allocation procedures produces network-wide inefficiencies that are only partially compensated by local optimization efforts, a conclusion emphasized in the EASA Regulatory Impact Assessment (RIA) (European Aviation Safety Agency, 2008), which documents persistent fragmentation, uneven oversight and systemic delay propagation across Member States. The RIA also stresses that rule-based processes-when decoupled from a system-level view-limit the ability to anticipate interactions among stakeholders, thus motivating the shift towards more integrated regulatory frameworks.

This concern aligns with a wider literature on delay propagation in air transport, which shows that delay is not a linear local phenomenon but a network effect amplified by interdependencies among airspace sectors, airports and airlines (Cook et al., 2004). Studies on the effectiveness of Functional Airspace Blocks and Single European Sky (SES) initiatives have demonstrated that fragmented governance structures tend to perpetuate structural inefficiencies (Button and Neiva, 2013; Buyle et al., 2020), with measurable consequences for delay levels, cost performance and service quality. The organizational and regulatory complexity of SES has therefore encouraged the search for mechanisms that balance efficiency and equity while respecting institutional constraints (European Aviation Safety Agency, 2008; Efthymiou and Papatheodorou, 2018). The underlying question is whether different forms of adaptive control could better manage demand-capacity imbalances than static regulations designed primarily for fairness and non-discrimination (Künne et al., 2023).

A related ATM literature seeks to improve performance not only by regulating demand, but also by increasing the flexibility of capacity provision itself in time and/or space. One stream studies dynamic sector configuration and sectorisation, in which sectors are activated, merged, split, or re-partitioned to better match traffic patterns and balance controller workload (Sherali and Hill, 2013; Gerdes et al., 2018). Another stream relaxes the strict coupling between traffic and fixed sector ownership through sectorless or flight-centric concepts, allowing control responsibility to be allocated more flexibly in space (Schmitt et al., 2011). Complementarily, capacity-planning studies introduce temporal flexibility through sector-opening schemes and sector-hours under uncertainty (Starita et al., 2020). The CAEHO mechanism examined here is closest to the spatial-flexibility strand, because it preserves traffic trajectories and declared capacities while reallocating control responsibility for eligible outbound aircraft to neighbouring sectors with spare capacity.

Beyond this internal ATM literature, a fruitful parallel emerges from surface-transportation control, particularly the well-established practice of ramp metering (Levinson and Zhang, 2006) and the more recent advances in cordon metering (Doig et al., 2024). Ramp metering regulates the inflow of vehicles into a motorway so as to prevent flow breakdown, stabilize throughput and reduce total delay on the mainline. The (Mizuta et al., 2014) reported that metering substantially improves travel time, safety and emissions, while inevitably redistributing delay between ramp users and through-traffic, thereby creating clear winners and losers. Crucially, the same report highlights the institutional and political challenges generated by perceived unfairness and the need for transparent evaluation and stakeholder engagement in the implementation of adaptive control strategies.

This logic is conceptually relevant to air transport. Both ATM regulations and ramp-metering strategies embody a tension between local delay allocation and system-wide performance optimization. Evidence from ramp-metering field trials suggests that adaptive control strategies typically operate along an efficiency-equity frontier: improvements in aggregate performance may be accompanied by unevenly distributed burdens across user groups. These findings underline the importance of explicitly quantifying distributional impacts and incorporating governance considerations when evaluating algorithmic control mechanisms in shared infrastructure systems.

Evaluating such distributional impacts requires structured methodologies. Traditional cost-benefit analysis (CBA) provides a monetary valuation of performance changes but is often insufficient when externalities are non-monetizable or when multiple actors with divergent preferences are involved. The European Investment Bank's RAILPAG methodology (European Investment Bank (EIB), 2005) explicitly recognizes that transport projects must be assessed across economic, social, environmental and institutional dimensions and that different stakeholders experience these impacts asymmetrically. RAILPAG's multi-actor impact matrix has become a reference for systematic appraisal, providing a clear structure for identifying criteria, allocating weights and discussing trade-offs.

At the methodological frontier of multi-actor analysis, the MAMCA framework (Macharis et al., 2009) places stakeholders at the center of the evaluation process by deriving criteria directly from each stakeholder's objectives and combining qualitative and quantitative indicators in a transparent multi-criteria structure. MAMCA emphasizes early stakeholder engagement, explicit elicitation of criteria and weights, and the synthesis of alternative rankings across actors. Subsequent developments, such as criteria-preprocessing approaches for large-scale participatory evaluations (Huang et al., 2023), refine this logic by formalizing the selection of relevant criteria and ensuring cognitive manageability for participants. These methodological innovations are applicable to the air-transport context, where stakeholders include airlines, airports, passengers, ANSPs and regulators.

Beyond multi-criteria approaches, the literature has also clarified the role of multi-actor decision analytics for resolving conflicts in infrastructure planning. Carlos A. (2001) provides a rigorous framework for identifying vertical and horizontal conflicts across policy units and integrating value-based models with spatial equity considerations. Such analyses are instructive for ATM regulation, where local decisions frequently carry consequences across regional and national boundaries.

These analytical traditions intersect with the economic evaluation of delay. The Eurocontrol cost-of-delay framework, originating from Cook et al. (2004) and subsequently updated in the Standard Inputs for Economic Analyses of Eurocontrol (2024), provides monetary estimates for the delay costs borne by airlines and passengers. Recent works have shown that extending such monetary valuation to other stakeholders is methodologically fragile. Delgado et al. (2021) demonstrate that economic severity can be assessed

reliably only at an aggregated aviation-system level because cost attribution beyond airlines involves strong assumptions, and Gurtner and Bolić (2023) show that even airlines often lack reliable internal cost estimates and rely on approximations. Both studies highlight the difficulty of deriving consistent monetary delay costs for airports or ANSPs. This reinforces the need for hybrid evaluation frameworks in which airline and passenger impacts are monetized, while airport and ANSP impacts are represented through qualitative or proxy indicators.

Finally, regulatory perspectives from outside the ATM domain reinforce the need for structured impact assessment. The EASA RIA (European Aviation Safety Agency, 2008) for the extension of ATM/ANS competencies offers a comprehensive example of multi-criteria policy evaluation grounded in safety, economic, environmental and institutional indicators. Its diagnosis of fragmentation and uneven oversight further supports the idea that stakeholder-oriented evaluation is essential for the governance of complex, multi-actor infrastructure systems.

In parallel to these regulatory and economic discussions, a distinct strand of research has examined adaptive modifications of airspace configuration under the Airspace Management (ASM) process. Dynamic sectorisation has been proposed as a mechanism to modify sector boundaries and regroup atomic air blocks in response to predicted workload and traffic demand. Ehrmanntraut and McMillan (Ehrmanntraut and McMillan, 2007) describe dynamic sectorisation as part of Strategic Traffic Organisation, where sector geometries are reconfigured to increase overall centre capacity. More recently, AI-based approaches combine workload prediction, clustering and optimization techniques to redesign sector boundaries in a data-driven manner (Xu et al., 2024). These contributions explicitly alter the geometric structure of operational sectors and therefore align with structural airspace configuration within the ASM layer.

By contrast, operational research in ATM has explored adaptive demand-capacity balancing mechanisms that operate without modifying sector geometry, including early handover and sector-level coordination strategies (Borràs et al., 2024; Borràs et al., 2025; Borràs et al., 2026). These mechanisms preserve predefined sector topology and redistribute aircraft control responsibility across existing interfaces. As such, they are operationally aligned with the ATFCM layer, where demand is managed relative to an established structural configuration. However, while these studies demonstrate the feasibility of algorithmic workload redistribution and sector-level performance improvements, they remain primarily focused on operational metrics rather than stakeholder-level economic and distributional evaluation.

Taken together, the literature provides three core insights. First, delay propagation in air transport is inherently network-driven; regulatory instruments that ignore these interdependencies may amplify downstream disruptions and increase total system-wide delay costs. Second, adaptive control mechanisms—illustrated by ramp metering—can outperform static allocation rules but raise efficiency-equity trade-offs that require explicit assessment. Third, multi-actor evaluation frameworks and delay-cost modeling tools provide methodological building blocks for stakeholder-oriented appraisal.

However, despite these parallel developments, the economic implications of substituting selected ATFCM regulatory interventions with adaptive sector-level demand-capacity balancing mechanisms have not been systematically quantified. In particular, no study has integrated operational counterfactual simulation with stakeholder-level delay-cost analysis to examine the distributional and institutional consequences of such substitution within the European ATM framework. This gap motivates the analytical approach developed in the present paper.

3. Data and methods

This section provides an overview of how airspace demand and capacity are managed within the European air traffic management system. It outlines the main operational phases and measures used to anticipate, monitor, and mitigate imbalances between traffic demand and controller workload, setting the context for the subsequent analysis of proactive mechanisms such as the CAEHO approach.

3.1. Airspace demand-capacity balancing background

Demand–capacity balancing in the European Air Traffic Management (ATM) system is governed by two interrelated but institutionally distinct processes: Airspace Management (ASM) and Air Traffic Flow and Capacity Management (ATFCM). Under the Flexible Use of Airspace (FUA) concept (EUROCONTROL, 2015), ASM defines and allocates airspace structures, while ATFCM manages traffic demand relative to the capacity resulting from those structural decisions (Mihetec et al., 2011; EUROCONTROL, 2023a).

ASM operates across three levels. ASM Level 1 (strategic) establishes airspace design, sector configurations, and high-level rules of use months or years in advance. ASM Level 2 (pre-tactical) performs day-to-day airspace, selecting among predefined configuration scenarios. ASM Level 3 (tactical) manages real-time airspace activation, deactivation, or temporary reallocation during operations. These structural decisions define the capacity envelope within which traffic is managed.

In parallel, ATFCM manages traffic demand across strategic, pre-tactical and tactical phases. Strategic ATFCM anticipates seasonal traffic evolution and coordinates capacity planning in cooperation with Network stakeholders. Pre-tactical ATFCM refines traffic forecasts and adjusts flow measures in the days preceding operations. Tactical ATFCM monitors real-time traffic evolution and implements corrective measures when demand exceeds declared capacity. Although ASM and ATFCM have distinct responsibilities, their timelines overlap operationally: ASM shapes structural capacity, while ATFCM adjusts demand relative to that capacity through the Network Operations Plan (NOP) and collaborative decision-making processes.

Within this governance framework, capacity imbalances may still arise despite strategic planning and sector configuration adjustments. Real traffic trajectories rarely match forecasts with full accuracy, and uncertainty increases as operations approach execution

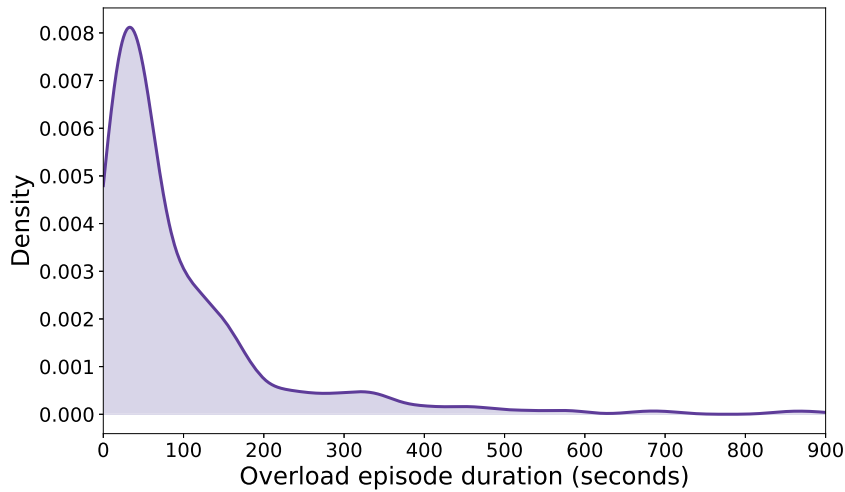


Fig. 1. Kernel density estimate of overload episode durations on 27 July 2024. ECAC area.

time. During the tactical phase, sudden demand peaks, meteorological disruptions, or trajectory deviations may generate local overload situations.

Empirical observation of en-route operations shows that many overload situations are short-lived, frequently lasting only a few minutes before demand naturally rebalances.

Fig. 1 illustrates the empirical distribution of expected overload episode durations identified on 27 July 2024 across all active en-route sectors in the European Civil Aviation Conference (ECAC) area, based on planned demand relative to declared capacity. The density is strongly concentrated within the first minutes of each episode, indicating that a large share of overload events are short-lived. This ECAC-wide evidence reinforces the temporal mismatch between disturbance duration and structural reconfiguration measures, which typically involve configuration transitions and resource redeployment processes that operate on longer time scales.

In such transient regimes, structural measures such as sector splitting or boundary redesign would require configuration transitions, controller reassignment, and coordination efforts that may be disproportionate to the duration of the imbalance. This temporal mismatch between disturbance duration and structural intervention motivates the analysis of marginal, flight-level redistribution mechanisms that can provide short-term elasticity without altering the prevailing sector configuration.

To correct short-term demand-capacity mismatches, Short Term ATFCM Measures (STAM) are applied. These include tactical rerouting, flight level capping and spacing instructions, which support coordination between the Network Manager and local air traffic control units (ENAI, 2015; SESAR Joint Undertaking, 2022). When such measures are insufficient, ATFCM implements regulations that can affect aircraft already airborne or still on the ground. Ground regulations delay departures in order to limit the inflow of traffic into overloaded sectors or airports.

Regulations constitute a formal ATFCM instrument designed to preserve safety by aligning demand with declared capacity. However, by introducing departure delays, they may trigger delay propagation across rotations. From an economic perspective, regulatory delay therefore represents a measurable and monetizable outcome of demand–capacity balancing decisions, affecting airlines and passengers directly, and indirectly influencing airport and ANSP operations.

Within this institutional context, proactive balancing mechanisms such as the Clusterized Aircraft Early Handover (CAEHO) can be interpreted as complementary operational tools. CAEHO does not modify sector geometry or structural airspace design as defined within the structural planning phases of ASM. Instead, it operates at the tactical interface between ASM and ATFCM tactical flow management by redistributing control responsibility for selected aircraft across existing sector boundaries. By reducing local workload peaks before regulatory thresholds are reached, such mechanisms may decrease reliance on reactive ATFCM regulations while preserving the established structural framework.

3.2. The CAEHO mechanism

The CAEHO mechanism has been described and analyzed in previous contributions (Borràs et al., 2025; Borràs et al., 2024, 2026; Borràs et al., 2026). For completeness, the main operational elements relevant to the present economic evaluation are summarized below.

CAEHO supports proactive workload reduction by transferring communications and control of groups of eligible en-route aircraft to adjacent sectors that have available capacity. Only flights that are conflict-free and have a suitable remaining dwell time inside the overloaded sector are considered. Candidates must be far enough from the boundary to allow coordination yet close enough to ensure predictable trajectories, which in practice corresponds to a short time window before exit. The remaining dwell times considered for the analysis, and for an aircraft to be eligible as a CAEHO candidate, have been set to 300, 360, 420, and 480 s. Specifically, in a microscopic analysis carried out on a sector-by-sector basis, the appropriate remaining dwell time must be defined individually

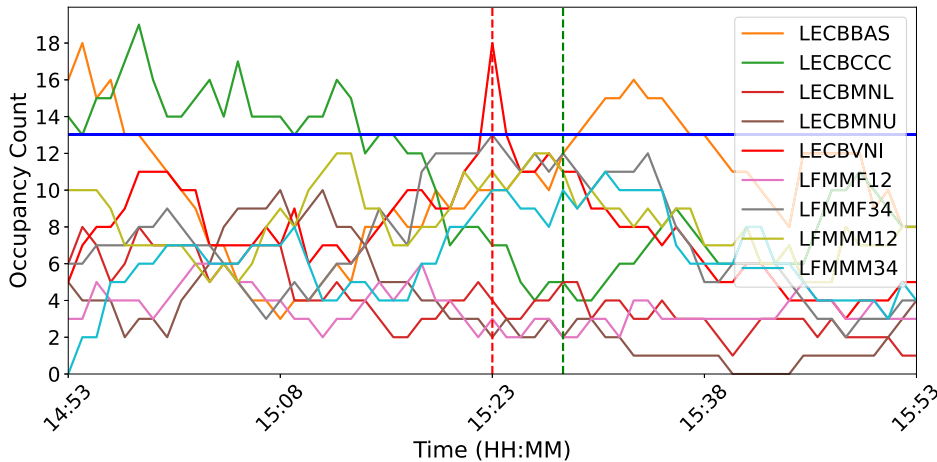


Fig. 2. LECBVNI sector and its adjacent sectors occupancy count from 14:53 to 15:53 on 27 July 2024.

for each sector to ensure realistic eligibility conditions. The mechanism applies only in the en-route environment above FL240 and requires that the downstream sector be active and able to safely absorb the additional workload. By delegating coherent clusters of aircraft rather than individual flights, CAEHO improves coordination efficiency, prevents overload peaks, and reduces the likelihood of disruptive capacity measures while maintaining safety and continuity of service (Borràs et al., 2026).

The core principle of CAEHO is the delegation of communications and control responsibility for coherent clusters of aircraft. Previous work by Borràs et al. (2025) has explored alternative implementation variants of the CAEHO, including delegation of entire airblocks and delegation of flexible sub-areas, approaches that share conceptual similarities with Dynamic Airspace Configuration (DAC) or Dynamic Airspace Sectorization (DAS). That study discusses the respective advantages and limitations of these methodological options and outlines their potential interaction with structural airspace configuration processes. However, a comprehensive benchmarking among these variants and traditional dynamic sectorization approaches is still ongoing and is beyond the scope of the present paper. In this study, the analysis focuses exclusively on the cluster-based delegation mechanism as the operational core of CAEHO in order to isolate and evaluate its economic and distributional implications under a fixed sector configuration.

While the mechanism can operate through a single-cluster transfer toward one neighbouring sector, realistic operational contexts may require more complex coordination patterns. Overload situations are not always resolved through a single cluster delegation; instead, multiple clusters may need to be transferred, potentially toward different adjacent sectors. Such multi-cluster and multi-sector configurations increase coordination complexity and constitute the operational context in which structured algorithmic support becomes most relevant. The CAEHO framework is designed to address these scenarios through coordinated and capacity-constrained decision logic.

The spatio-temporal interdependencies among overloaded sectors must be identified, with particular attention to the timing of peak overload. Once the minimum number of aircraft whose control will be delegated is determined, the available spare capacity in neighbouring sectors is evaluated. For instance, on 27 July 2024 at 15:23, the LECBVNI sector experienced an overload. The exceedance in this sector and the spare capacity in the surrounding sectors were analysed to assess delegation feasibility, as illustrated in Fig. 2.

The LECBVNI configuration is presented solely as an illustrative example of a single CAEHO delegation event, intended to clarify the mechanics of the procedure. The quantitative results reported in the remainder of the paper are derived from the network-wide evaluation of all overload episodes identified during the full operational day.

It can be observed in Fig. 2 that the instantaneous occupancy count of the overloaded sector (in red) exceeds its declared maximum occupancy (18 versus 13). The blue horizontal line denotes this declared occupancy limit. The remaining dynamic lines illustrate the temporal evolution of the occupancy counts in the adjacent sectors. For clarity, the horizontal lines corresponding to the declared maximum occupancy of the adjacent sectors have been omitted. By means of this representation, spatio-temporal relationships can be established, as they constitute the primary indicator for assessing whether the CAEHO mechanism can be triggered or not.

Once spare capacity is confirmed, aircraft inside the overloaded sector are evaluated to determine their suitability for delegation. The cluster of candidates is defined according to their heading toward the adjacent sector, their remaining dwell time in the overloaded sector, and their conflict-free status. Only flights that follow a coherent outbound trajectory and do not present predicted conflicts with other traffic are included. This ensures that the receiving controllers can safely assume responsibility without additional coordination burden or risks to safety.

Spare capacity is considered operationally available only if, during the CAEHO activation time window, the projected occupancy of the receiving sector remains below 80% of its declared maximum capacity. This threshold is imposed as a safeguard to prevent secondary congestion and to ensure that early delegation does not transfer instability to neighbouring sectors.

Fig. 3 shows the CAEHO application for the LECBVNI sector during the overload detected on 27 July 2024 at 15:23.

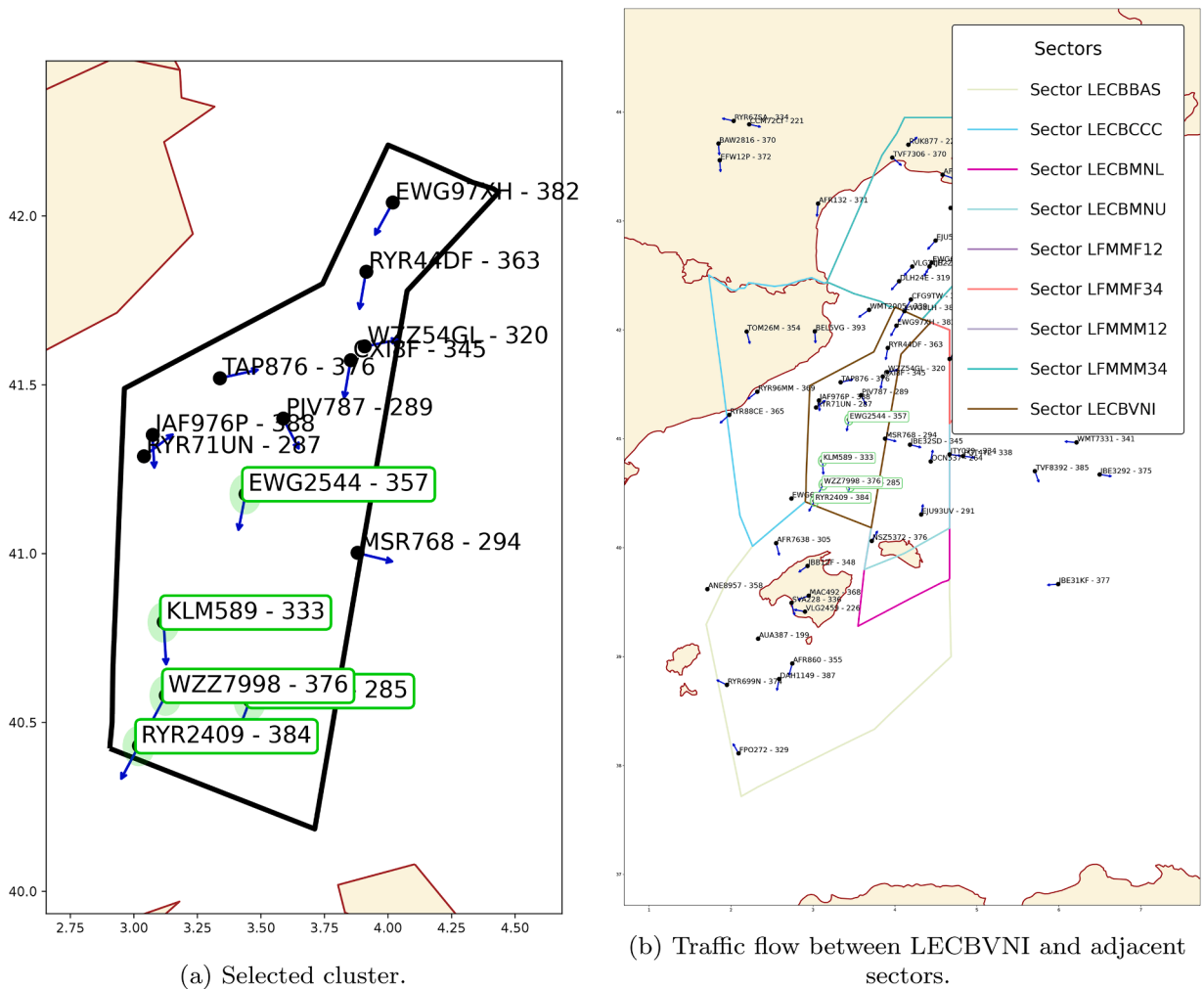


Fig. 3. LECBVNI sector flow and cluster on the 27 July 2024 at 15:23.

The figure includes sectors LECBVNI, LECBCCC, LECBMNL and LECBMNU, which belong to Barcelona ACC (ENAIRES airspace), as well as sectors LFMMF12, LFMM34, LFMMM12 and LFMMM34, which belong to Marseille ACC (DSNA airspace). This configuration illustrates that CAEHO is designed to operate not only across different sectors within the same ACC, but also across ACC boundaries and, consequently, across different ANSPs. Such cross-ACC and cross-ANSP coordination highlights the need for a certain level of operational interoperability and automation support. The required automation and decision-support mechanisms are currently being actively evaluated within the framework of the ANTICIPATE project (SESAR 3 Joint Undertaking, 2024).

In Fig. 3(a), the selected cluster of outbound aircraft is highlighted in green. These flights satisfy all eligibility conditions and are candidates for early delegation. Fig. 3(b) illustrates the traffic flow between LECBVNI and its adjacent sectors at the same moment. By transferring the control of the selected aircraft to LECBBAS, provided that this receiving sector has sufficient spare capacity, the projected occupancy of LECBVNI is reduced, thereby eliminating the peak exceedance at the trigger time. An ATFCM regulation is avoided only if the resulting occupancy profile remains at or below the declared capacity for the entire regulation period, meaning that all overload peaks that would otherwise occur within that window are eliminated. Under this condition, the regulation becomes unnecessary, associated ground delays are not generated, and network-level delay propagation is mitigated.

3.2.1. Operational and implementation considerations

While CAEHO demonstrates potential benefits in terms of overload mitigation and delay reduction, some operational barriers must be considered.

First, the mechanism requires real-time detection and characterization of sector overload conditions, including accurate short-term workload prediction. In parallel, spare capacity must be dynamically computed in all adjacent sectors, taking into account declared capacity limits and current occupancy levels.

Second, delegation is not limited to a single cluster. Multiple coherent aircraft clusters may need to be identified and transferred either simultaneously or sequentially, potentially toward different adjacent sectors. These transfers may occur within the same ACC or across ACC and ANSP boundaries, thereby increasing coordination complexity.

Third, eligibility assessment extends beyond verifying spare capacity and also requires validation of conflict-freeness and trajectory compatibility. Only aircraft that are predicted to remain conflict-free under the delegated control configuration are deemed transferable. This condition necessitates trajectory-based conflict detection checks, thereby increasing computational complexity relative to a purely capacity-based allocation rule. It is emphasized that all results reported in this study already incorporate the conflict-freeness constraint in addition to spare capacity verification.

Furthermore, when delegation involves sectors operated by different ACCs or ANSPs, specific Letters of Agreement (LoAs) defining coordination procedures, transfer conditions, liability aspects, and operational constraints would be required. The absence of harmonized LoAs could constitute a structural barrier to cross-ACC implementation.

Finally, the operational feasibility of CAEHO depends on the evolution of current Controller Working Position (CWP) services to support the reliable identification of eligible aircraft clusters and to ensure shared situational awareness among all involved ATCOs. Without adequate decision-support tools and interoperable systems, manual coordination would limit scalability within tactical time horizons.

3.3. Raw data

The proper implementation of the CAEHO mechanism requires precise information about the position of each flight at any given time, as well as the sector in which it is currently located. With this information, the algorithm can compute forecasted occupancies, identify potential overloads, and determine the occupancy levels not only of the overloaded sectors themselves but also of their adjacent sectors and of the downstream sectors to which the aircraft will proceed once they leave their current airspace. To obtain this information, planned flight trajectory data have been used and subsequently processed to derive the positional and sectoral information required for these calculations.

Trajectory data have been obtained from the Aeronautical Information Regulation and Control (AIRAC) database (ICAO, 2024). AIRAC provides airspace configuration and routes information, among others, and it is an essential mechanism to allow pilots, dispatchers, ATCOs, air traffic flow managers, flight management systems and aeronautical charts all sharing the same information, coming from a unique database, improving efficiency and safety.

The AIRAC cycles with validity between 11 July 2024 and 2 October 2024 were analysed to ensure configuration consistency and to identify the reference day based on regulatory intensity across the ECAC area.

The reference day selected for the analysis is 27 July 2024. All quantitative trajectory-based simulations and economic evaluations presented in this paper are conducted exclusively for this reference day. On that date, 32,714 flights operated within the Network Manager area (EUROCONTROL, 2024), making it representative of a high-demand summer traffic scenario.

The AIRAC dataset also provides detailed information about the regulations that were applied, including the affected sectors, the number of regulated flights, the associated delay, and the underlying cause of each regulation. These causes may include weather conditions, ATC-staffing shortages, military activity, special events, aerodrome capacity limitations, ATC-capacity constraints, or other factors. In this study, the focus is placed on the application of the CAEHO mechanism as a means to mitigate ATC-capacity regulations, which occur when the number of aircraft expected to enter or be controlled within a sector exceeds the maximum workload or traffic volume that air traffic controllers can safely manage. Consequently, only the data corresponding to ATC-capacity regulations have been considered.

3.4. Case description

This paper focuses on analyzing the impact of mitigating regulations due to ATC-capacity issued on 27 July 2024 within the European Civil Aviation Conference (ECAC) area. The ECAC, comprising 44 member states, constitutes the geographical framework for pan-European air traffic management and network performance analysis. The area considered in this study is represented in Fig. 4.

On 27 July 2024, a total delay of 74,089 min was recorded due to ATC-capacity regulations within the ECAC area. On that day, 14,628 flights were subject to regulation, of which 4137 experienced realized ATFCM delays. These figures illustrate the magnitude of network imbalances during the selected day.

During the analysed day, 1330 en-route sectors were active across the ECAC area, of which 122 were subject to ATC-capacity regulations. Among these regulated sectors, 87 generated effective ATFCM delays. Because ATFCM regulations are applied at sector level, these 87 delay-affected sectors constitute the baseline for the economic evaluation. Each overload episode within these sectors was processed using the same CAEHO configuration and delegation criteria, ensuring methodological consistency across the network.

The regulated sectors analysed in this study belong to multiple ACCs and are operated by different ANSPs across the ECAC area. Consequently, the evaluation framework implicitly considers both intra-ACC and cross-ACC adjacency configurations. When neighbouring sectors belonged to different ACCs or different ANSPs, delegation feasibility was assessed under the same operational safeguards. This ensures that the results are representative of a realistic pan-European operational environment rather than a single-ACC configuration.

The selection of 27 July 2024 is justified by the fact that, within the extended observation window (11 July-2 October 2024), it exhibited the highest regulatory intensity in terms of flights affected by ATC-capacity regulations. Evaluating CAEHO under these

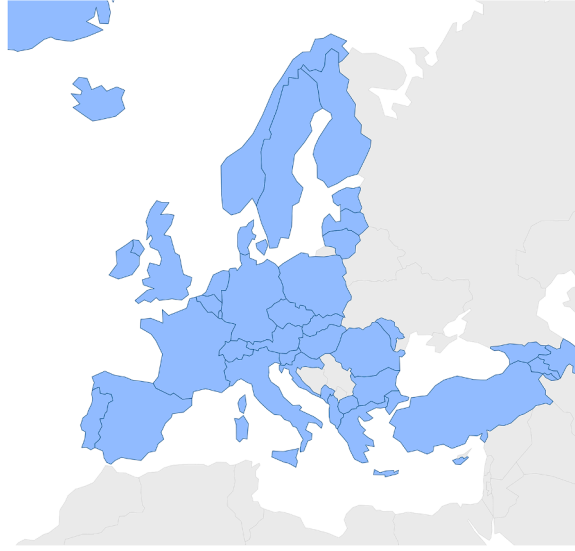


Fig. 4. ECAC countries map.

peak-demand conditions ensures that the assessment is conducted in a structurally congested network scenario, thereby providing a stringent and operationally representative benchmark rather than a moderate or low-impact case.

In addition, spatio-temporal adjacency between overloaded sectors was examined to identify multi-sector congestion configurations. Only eight adjacent sector-pair occurrences exhibited peak overload events within a 30 min interval on the analysed day, namely: EDUUSLN13-LSAZM4 (11:06-11:12), LFEEKHE-LSAZM5 (09:25-09:34), LIRROV-LIRRTS (08:24-08:35 and 11:48-11:57), LHKRKFOR-LWSSLOW355 (09:47-09:57 and 11:22-11:33), LECMPAU-LECMTLU (12:25-12:40), and EDUUERL12-EDUUFUL1U (10:58-11:22). These tightly coupled configurations represent a limited proportion of the regulated sectors and do not constitute the dominant overload pattern observed. All such cases were included in the CAEHO evaluation and processed under identical operational and capacity safeguards. The CAEHO framework allows chained early delegation across adjacent sectors when operationally feasible.

This network-wide dataset provides the empirical basis for assessing the potential of CAEHO to mitigate sector-level overload and reduce delay generation under realistic high-traffic conditions.

3.4.1. Stressing scenarios

In addition to the real data, which serve as the base scenario, a discrete-event simulation framework has been implemented to perform a resilience stress test of the CAEHO mechanism. This approach acknowledges that real-world traffic is inherently uncertain and highly sensitive to variations in demand and flow patterns. A stochastic approach to introducing uncertainty would consist of perturbing entry times or dwell times according to empirically calibrated distributions. Such approaches were preliminarily evaluated. However, stochastic perturbations alter the spatial and temporal configuration of overload events: peaks may shift, attenuate, disappear, or new peaks may emerge. In that case, the stressed scenario would no longer be directly comparable to the empirical baseline, and the performance of CAEHO could not be causally attributed to congestion intensity alone. Therefore, a controlled level of uncertainty is introduced into the simulation to assess the robustness of the mechanism under fluctuating conditions. However, neither the spatial nor temporal occurrence of overload events is modified; only the intensity of each existing peak is amplified. In this way, the stress test preserves the original traffic structure while progressively increasing the operational pressure acting on the system. The temporal location and duration of each overload episode therefore remain unchanged, while only the magnitude of the demand–capacity imbalance is amplified. This design isolates the effect of congestion intensity and eliminates confounding effects due to spatial or temporal traffic rearrangements.

Based on this approach, the stress scenarios considered in this study apply incremental amplifications of the peak magnitude ranging from 0 to 4. Values beyond this range would represent unrealistically over-stressed operational conditions. The magnitude of each synthetic peak amplification is denoted by δ . The stress parameter δ thus acts as a controlled amplification operator applied to existing exceedance peaks rather than as a stochastic traffic modifier.

Formally, let $O_s(t)$ denote the projected occupancy of sector s at time t , and let C_s denote its declared maximum capacity. The exceedance function is defined as:

$$E_s(t) = \max \{0, O_s(t) - C_s\}. \quad (1)$$

For each sector s and each time instant t such that $E_s(t) > 0$ in the empirical baseline, the stressed occupancy is defined as:

$$O_s^{(\delta)}(t) = C_s + E_s(t) + \delta, \quad \text{if } E_s(t) > 0, \quad (2)$$

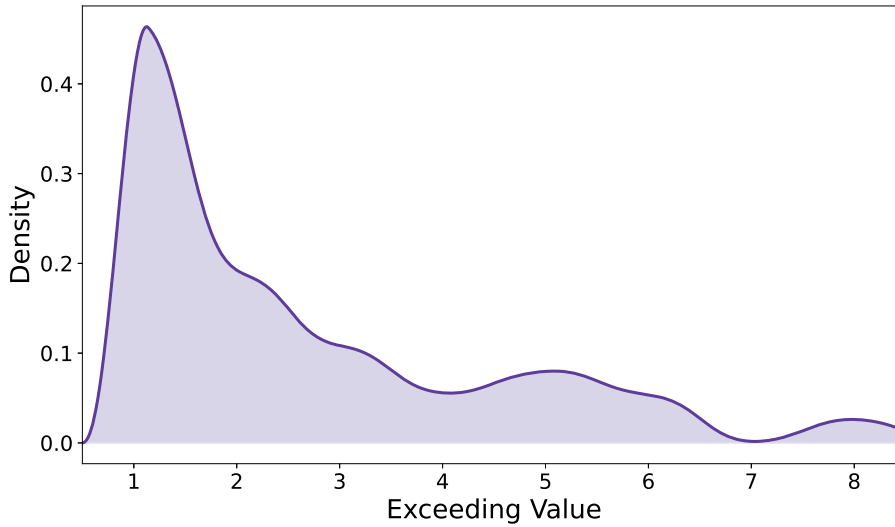


Fig. 5. Kernel density estimate (KDE) of exceedance magnitudes on 27 July 2024 across the ECAC area.

and

$$O_s^{(\delta)}(t) = O_s(t), \quad \text{if } E_s(t) = 0. \quad (3)$$

Thus, $\delta \in \{0, 1, 2, 3, 4\}$ represents an additive increment in the number of aircraft contributing to each empirically observed exceedance instant.

The amplification operator is applied systematically to all sector-time instants satisfying $E_s(t) > 0$ across the full set of empirically overloaded sectors on the reference day.

Fig. 5 depicts the empirical kernel density estimate of exceedance magnitudes aggregated across all overloaded sectors on 27 July 2024 within the ECAC area. The distribution is positively skewed and distinctly unimodal, with a dominant mode around one capacity unit and a pronounced decay in density beyond two units. Exceedance levels above three units lie in the upper tail of the distribution and represent a comparatively small fraction of observed overload events. The explored stress range up to $\delta = 4$ therefore extends into this upper tail, deliberately exposing CAEHO to congestion intensities that are statistically less frequent in the reference dataset.

It is important to emphasize that the objective of the stress scenarios is not to reproduce a fully stochastic propagation of uncertainty throughout upstream and downstream traffic flows. Such an objective would require a dynamic network-level simulation explicitly modelling trajectory interactions, delay propagation, and route adjustments. Instead, the present framework adopts a controlled sensitivity-analysis perspective: the aim is to evaluate the robustness of CAEHO under progressively intensified yet structurally comparable overload conditions.

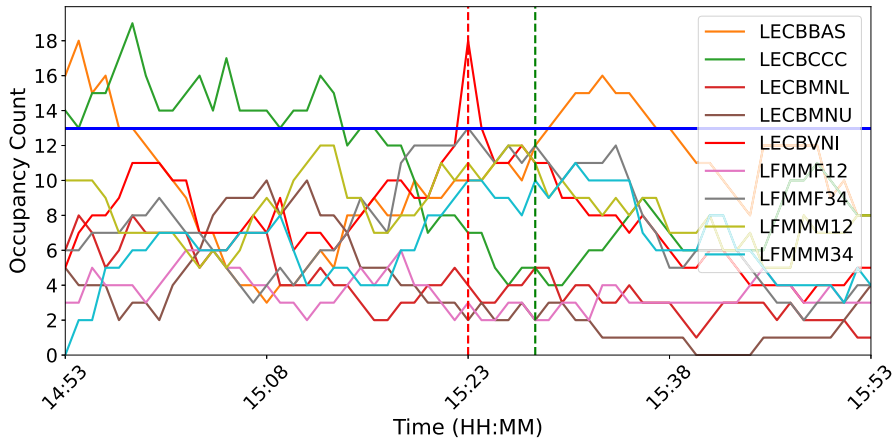
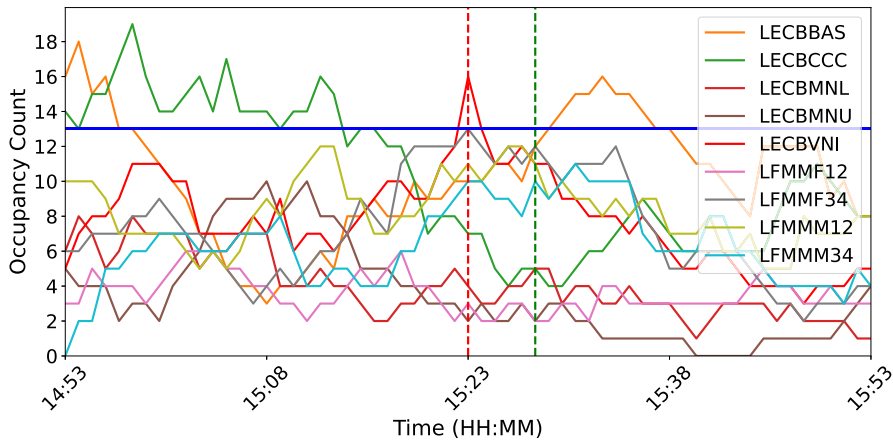
By holding spatial and temporal configurations constant and amplifying only exceedance magnitude, the stress design modifies a single structural variable. This one-factor perturbation enables a causal interpretation of performance variations with respect to congestion intensity. Importantly, the amplification is applied systematically across all overloaded sectors of the ECAC area on the analyzed day rather than selectively to favorable cases. As a result, the stress test constitutes a conservative robustness assessment.

Fig. 6 illustrates the practical effect of the amplification operator for the LECBVNI sector, which is presented solely for visualization purposes. The upper panel corresponds to $\delta = 4$, while the lower panel shows $\delta = 2$. In both cases, the temporal location and duration of overload episodes remain unchanged. Only the magnitude of the demand–capacity exceedance increases with δ . The peak positions and structural configuration are therefore preserved across stress levels, confirming that the stress design modifies congestion intensity without altering the underlying spatial–temporal traffic pattern.

3.5. Cost of delay

The cost of delay is a central component of the impact assessment because regulatory mechanisms in air-traffic management redistribute time penalties across stakeholders to prevent sector overloads. A large body of work (Cook et al., 2004; Eurocontrol, 2024) provides established monetary reference values for delay. Delays impose heterogeneous effects: passengers experience increased travel time and missed connections; airlines incur tactical and strategic costs; airports face operational inefficiencies; and ANSPs must manage higher workload, sector reconfigurations, and inefficiencies linked to reactionary flow patterns. Understanding these differentiated impacts is essential when assessing alternative demand-capacity balancing strategies.

In this study, en-route delay refers specifically to the delay imposed through ATC-capacity regulations when demand exceeds declared sector capacity. Because these regulations represent a deliberate administrative intervention to prevent overload, they are fully avoidable when the underlying demand-capacity imbalance is eliminated. Under an adaptive balancing regime that maintains

(a) LECBVNI occupancy with $\delta = 4$.(b) LECBVNI occupancy with $\delta = 2$.**Fig. 6.** LECBVNI occupancy under different stress-level scenarios.

capacity feasibility, ATC-capacity regulations are no longer required and their associated delays disappear. The removal of regulation-induced delay is therefore directly attributable to improved capacity management and does not imply the elimination of other tactical en-route delays, such as those resulting from weather or vectoring.

It is important to distinguish between a regulated flight and a delayed flight within the ATFCM framework. Being subject to a regulation does not necessarily imply the imposition of positive delay minutes. Empirical studies explicitly separate regulation status from delay magnitude and show that a flight may be regulated without incurring recorded ATFCM delay (Mas-Pujol and Delgado, 2024). Regulation assignment and realized delay therefore constitute analytically distinct elements of the ATFCM process.

Delay accounting in this study follows the attribution structure provided in the AIRAC-based operational dataset, whereby a flight affected by multiple simultaneous ATFCM regulations is associated with the delay of its most penalizing regulation only. Secondary regulation components are not reported with separate delay values in minutes. This attribution structure is commonly adopted in ATFCM delay studies (Sanaei et al., 2021). Consequently, the present analysis estimates avoided delay at regulation level, consistent with the available data, and does not reconstruct secondary delay components or perform dynamic network re-slotting. The reported results therefore represent avoided regulation-attributed delay under the established reporting framework rather than a full re-optimization of multi-regulated flight schedules.

A regulation is classified as avoidable only if all exceedance instants occurring during the full temporal duration of that regulation are eliminated by CAEHO under the stated operational safeguards. In other words, the sector occupancy must remain at or below its declared maximum capacity for the entire time window covered by the regulation. For regulations satisfying this condition, avoided delay is computed as the sum of the regulation-attributed delay minutes reported in the AIRAC dataset.

Importantly, CAEHO does not generate additional traffic demand in downstream sectors. Aircraft selected for early delegation are already planned, according to their filed trajectory, to enter the receiving sector. The mechanism anticipates the transfer of control

Table 1
Cost assumptions used in the study.

Concept	Value	Source
Share of business passengers	20%	(Chapman and Pot, 2025)
Share of non-business passengers	80%	(Chapman and Pot, 2025)
VoT of business passengers	54.56 €/hour	(Eurocontrol, 2024)
VoT of non-business passengers	22.34 €/hour	(Eurocontrol, 2024)
Average value of time (AVoT)	0.48 €/min	Computed from above values
Airline strategic delay cost - En-route	82.95 €/min	(Eurocontrol, 2024)

responsibility by a limited time window, but it does not modify routing, sector sequence, or total sector demand. The aggregate traffic volume of downstream sectors therefore remains unchanged.

Furthermore, early delegation is authorized only when the projected occupancy of the receiving sector remains below 80% of its declared maximum capacity throughout the activation window. This safeguard ensures that delegation does not create secondary overload conditions or trigger new ATC-capacity regulations downstream. Under these conditions, CAEHO redistributes workload temporally within available capacity margins rather than altering network topology or inducing new congestion dynamics.

Accordingly, the reported avoided-delay values represent avoided regulation-attributed delay under capacity-feasible sector interactions. The analysis does not attempt to re-simulate network-wide re-slotting or endogenous re-optimization of ATFCM measures. The results should therefore be interpreted as a conservative and data-consistent estimate of delay imposed by avoidable ATC-capacity regulations, rather than as a full dynamic network reconfiguration.

Passenger delay costs are typically expressed as a value of time (VoT), often measured per hour of travel time lost. Delay impacts are non-linear: a 180 min disruption does not merely triple the disutility of a 60 min delay. Longer delays generate discontinuities in utility-missed connections, re-accommodation, or overnight disruptions-that increase the opportunity cost sharply. Although aviation-specific evidence is limited, behavioral studies consistently document this non-linearity. The Eurocontrol Standard Inputs (Eurocontrol, 2024) acknowledge this pattern indirectly by distinguishing marginal delay from reactionary delay. Recent analyses of passenger profiles in Europe show that business travelers represent only around 20% of total passengers, with leisure and VFR traffic dominating demand (Chapman and Pot, 2025). Based on this evidence, we assume a 20% share of business passengers and compute an average value of time (AVoT) of 29.0€/h ($\approx 0.48\text{€/min}$) using the Eurocontrol VoT values Table 1.

For airlines, delay costs combine tactical and strategic components. Tactical costs refer to additional fuel burn, crew time, maintenance, and operational adjustments, and are well captured in Cook et al.'s estimates (Cook et al., 2004). Strategic costs arise when airlines embed buffers, adjust rotations, or allocate reserve aircraft at critical nodes. These represent capital costs: buffers immobilize productive assets, reducing aircraft utilization, while spare capacity increases fixed costs. Delay propagation amplifies these effects: delays incurred early in the day tend to propagate through subsequent flights operated by the same aircraft, increasing the likelihood and magnitude of later delays within the schedule (Churchill et al., 2010). Because ATFCM regulations impose delays pre-departure to avoid sector overload, they directly reduce aircraft utilization and trigger strategic inefficiencies. For this reason, airline delay savings in this study are valued using the strategic delay cost coefficients from the Eurocontrol Standard Inputs (Eurocontrol, 2024). These values reflect the economic impact of regulation-induced en-route delays on fleet utilization, capital productivity, and crew efficiency more accurately than tactical coefficients Table 1. Eliminating ATFCM regulations therefore corresponds directly to a reduction in strategic delay for airlines.

To account for heterogeneity across fleets, airline strategic delay savings are valued using aircraft-specific en-route strategic delay costs from Table 16.4 of the EUROCONTROL Standard Inputs (Eurocontrol, 2024), rather than a single network-average value. For aircraft types explicitly reported in Table 16.4, the corresponding unit cost is applied directly. For aircraft not listed in that table, the closest available aircraft is used as proxy. Appendix Table A.1 reports the mapping between the aircraft codes observed in the dataset, the selected EUROCONTROL proxy, and the resulting cost in €/min used in the calculations. This approach preserves consistency with the official EUROCONTROL valuation framework while introducing aircraft-level differentiation in the estimation of airline strategic delay savings. The network-average value is retained only as contextual information and is not used in the flight-level valuation.

Airports bear costs through increased reactionary operations, congested turnaround processes, gate conflicts, and reduced schedule predictability. While these effects are operationally significant, no standardized monetary valuation exists. Airport impacts depend strongly on local resource configurations, ground-handling contracts, and delay-absorption practices, and are therefore not included in Eurocontrol's monetary cost model. Consistent with the findings of Delgado et al. (2021), who emphasize the difficulty of attributing delay costs to non-airline actors, airport impacts in this study are assessed qualitatively, focusing on changes in operational stability and stand utilization.

For ANSPs, delay manifests through increased workload, higher sector complexity, and more frequent tactical interventions. Eurocontrol does not provide a dedicated ANSP cost of delay, reflecting the fact that ATFCM regulations do not directly alter ANSP cost bases-staffing levels and infrastructure provisioning remain largely unchanged in the short run. However, irregular demand profiles increase supervisory coordination and create inefficiencies in sector configuration. Reducing ATFCM regulations therefore decreases the operational burden on controllers and improves sector efficiency. As with airports, these impacts are captured qualitatively in the analysis rather than monetized.

Across all actors, the study adopts a common quantification logic: the benefits of avoiding ATFCM regulations are assessed by valuing the time saved for those stakeholders for whom reliable monetary coefficients exist (see Table 1). Airline savings are therefore

computed using the strategic delay cost values from Eurocontrol, and passenger benefits are valued using the average value of time derived from the Eurocontrol Standard Inputs (Eurocontrol, 2024). By contrast, airport and ANSP effects are represented qualitatively, as the literature shows that actor-specific monetary coefficients are either unavailable or cannot be derived without strong and often unrealistic assumptions. As highlighted by Delgado et al. (2021) and reinforced by Gurtner and Bolić (2023), cost of delay estimation remains fundamentally airline-centric, and attempts to extend it to other stakeholders are methodologically fragile. The adopted approach therefore provides a consistent, transparent and conservative estimation of benefits while preserving analytical rigor.

3.6. Fleet-equivalent utilisation proxy for strategic airline savings

In addition to monetising airline time savings using Eurocontrol delay-cost coefficients, the assessment reports a strategic “fleet-equivalent” proxy that expresses avoided ATFCM regulation delay in capacity terms. The objective is to translate dispersed delay minutes into an interpretable measure of how much deployed aircraft-time could be freed in an average sense (e.g., reduced buffer and reserve needs), without implying a literal short-run fleet reduction.

The proxy combines two data sources: (i) airline-specific avoided ATFCM regulation delay from the simulation and (ii) airline-specific airborne profiles derived from the observed daily flight list. Let $n_{a,h}$ denote the number of aircraft of airline a airborne during hour h . The deployed ECAC fleet for airline a is approximated by the peak airborne count N_a :

$$N_a = \max_h n_{a,h} \quad (4)$$

and total airborne aircraft-hours H_a are computed as:

$$H_a = \sum_h n_{a,h} \quad (5)$$

This yields an empirical airborne utilisation per deployed aircraft-day u_a :

$$u_a = \frac{H_a}{N_a} \quad (6)$$

For each scenario (δ, T) , let $D_a(\delta, T)$ denote total avoided ATFCM regulation delay minutes for airline a . Converting to hours and scaling by u_a gives the fleet-equivalent saving,

$$F_a(\delta, T) = \frac{D_a(\delta, T)}{60 u_a} \quad (7)$$

F_a can be interpreted as the number of “average deployed aircraft” whose airborne utilisation would be freed if the avoided delay were consolidated into usable capacity. Because tail numbers are not observed and peak airborne is a lower bound on the number of aircraft actually used during the day, the resulting fleet-equivalent values should be interpreted conservatively.

3.7. Seats per aircraft and passenger load factor assumptions

Monetising passenger time benefits requires an estimate of passenger volumes on each flight affected by regulation-induced delay. Because flight-level bookings are not available in the AIRAC regulation dataset, passenger counts are approximated using aircraft seat capacity and a single passenger load factor (LF). For the peak-summer reference day analysed here, we adopt $LF = 0.88$, which is the rounded Europe-wide passenger load factor reported by IATA for July 2024 (88.2%) (International Air Transport Association, 2024b). This value is consistent with the corresponding August 2024 Europe-wide value (International Air Transport Association, 2024a) and remains above the 2024 Europe-wide annual value (84.8%) (International Air Transport Association, 2025), which supports its interpretation as a summer benchmark rather than a year-round average. Passenger exposure is therefore approximated as $p_i = seats_i \times 0.88$ for flight i .

3.8. Impact assessment methodology

The objective of the impact assessment is to translate the operational outcomes of the CAEHO simulations (avoided ATC-capacity regulation delay minutes, avoided delayed flights, and avoided regulated flights) into stakeholder-relevant impacts. Consistent with stakeholder-oriented appraisal traditions in transport policy (e.g., RAILPAG and multi-actor evaluation frameworks), the assessment is structured as a stakeholder impact matrix that distinguishes (i) impacts that can be monetised using robust, widely adopted unit values and (ii) impacts that are assessed through operational-efficiency or proxy indicators when direct transferable monetary coefficients are unavailable or methodologically fragile.

The analysis compares the regulatory baseline (existing ATFCM regulations for ATC-capacity) with CAEHO-based balancing under different remaining dwell-time thresholds $T \in \{300, 360, 420, 480\}$ s and stress levels $\delta \in \{0, 1, 2, 3, 4\}$.

The selected values correspond to a tactical horizon of 5 to 8 min, which is operationally compatible with coordination and early transfer actions while remaining short enough to limit uncertainty in conflict evolution. The uniform 60 s increment provides a structured sensitivity analysis of the effect of enlarging the CAEHO window, rather than relying on isolated thresholds. Moreover, this range is consistent with the empirical dwell-time distribution observed across sector-entry records in the ECAC area on 27 July 2024, where dwell times are frequently concentrated within a few minutes. Consequently, varying T within this band produces a meaningful

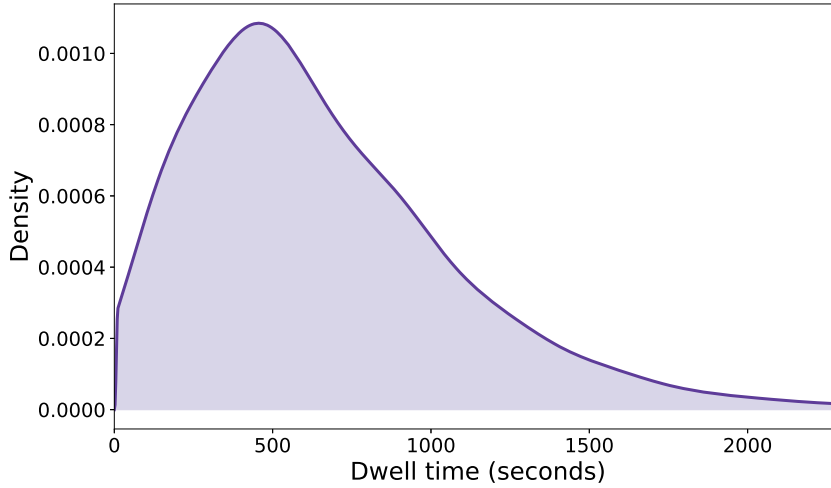


Fig. 7. Kernel density estimate (KDE) of sector-entry dwell times across the ECAC area on 27 July 2024.

modulation of the eligible candidate pool without extending the delegation horizon to durations where the conflict-free assumption becomes progressively less reliable.

Fig. 7 reports a kernel density estimate (KDE) of sector-entry dwell times for the ECAC area on 27 July 2024, obtained by pooling sector-entry records whose intervals overlap published opening slots. The density is concentrated in the short-duration region and decays with a pronounced right tail, indicating that long sector traversals exist but are comparatively less frequent. The evaluated window range $T \in \{300, 360, 420, 480\}$ s is therefore aligned with the high-density portion of the observed dwell-time distribution, so that the sensitivity study explores practically relevant values for which candidate availability is non-trivial while the forecasting horizon remains bounded. Sector-specific differences in geometry and traffic patterns still imply heterogeneous dwell-time regimes; for this reason, T is not claimed to be universally optimal but is treated as a controllable tactical parameter whose impact is quantified through the multi-sector, day-wide evaluation.

For each scenario, the simulation outputs a flight-level estimate of avoided regulation-induced en-route delay (in minutes). In line with Section 3.5, this study values only the delay that is directly attributable to ATFCM regulations issued due to sector overload. Other sources of en-route delay (e.g., weather, vectoring) are outside the scope of the quantification.

For airlines and passengers, impacts are monetised using the cost coefficients reported in Table 1. Airline benefits are computed as avoided delay minutes multiplied by Eurocontrol's strategic en-route delay cost coefficient. Passenger benefits are computed as avoided passenger-minutes (estimated passengers per flight multiplied by avoided delay minutes) multiplied by the average value of time (AVoT). This yields a transparent, conservative monetisation layer grounded in standard inputs.

For airports and ANSPs, impacts are assessed primarily through non-monetary operational and proxy-based indicators rather than through direct economic valuation. The literature shows that cost-of-delay valuation is fundamentally airline-centric and that extending monetary coefficients to airports and ANSPs requires strong assumptions that are not transferable across contexts (Delgado et al., 2021; Gurtner and Bolić, 2023). Moreover, removing ATFCM regulations does not mechanically reduce the short-run cost base of airports or ANSPs, since staffing and infrastructure costs remain largely fixed in the short term.

Consequently, airport and ANSP impacts are represented through proxy and operational-efficiency indicators such as changes in the number of regulated flights, changes in delayed flights, temporal redistribution of avoided regulation delay (Section 4.2), and downstream operational-capacity utilization metrics.

Airport impacts are quantified through non-monetary proxy indicators that measure the amount of regulation-induced disruption removed from each airport's departure and arrival streams. Because no transferable monetary unit cost is available for airport delay impacts, the objective is not to estimate airport financial savings, but to quantify airport-level exposure to avoided ATFCM regulation effects.

For each flight i for which a regulation-induced delay is avoided by CAEHO, let d_i denote the avoided delay minutes, o_i the departure airport, and r_i the arrival airport. The avoided departure-side incidence for airport a is defined as:

$$I_a^{dep} = \sum_i \mathbf{1}(o_i = a) \quad (8)$$

and the avoided arrival-side incidence as:

$$I_a^{arr} = \sum_i \mathbf{1}(r_i = a) \quad (9)$$

The corresponding avoided delay exposure minutes are:

$$D_a^{dep} = \sum_i d_i \mathbf{1}(o_i = a) \quad (10)$$

and:

$$D_a^{arr} = \sum_i d_i \mathbf{1}(r_i = a) \quad (11)$$

Total airport incidence exposure is then obtained as:

$$I_a^{tot} = I_a^{dep} + I_a^{arr} \quad (12)$$

$$D_a^{tot} = D_a^{dep} + D_a^{arr} \quad (13)$$

These indicators assign one avoided regulation-impact incidence to the departure airport and one to the arrival airport of each affected flight. The same logic is applied to avoided delay minutes. This attribution should not be interpreted as a direct monetary airport saving or as a literal reduction in airport operating time. Rather, it measures the amount of regulation-induced schedule disruption removed from the airport's operational streams. Departure-side exposure is associated with improved off-block, runway-departure and turnaround predictability, whereas arrival-side exposure is associated with improved arrival-stream regularity, stand planning and downstream connection stability.

The airport-level indicators reported in this study are absolute exposure measures. They quantify the number of avoided regulation-impact incidences and the corresponding avoided regulation-delay minutes attributed to each airport's departure and arrival streams. These indicators identify where the largest amount of regulation-induced disruption is removed from the airport network. Since the objective is to quantify the spatial distribution of avoided airport exposure rather than to rank airports by relative intensity, no normalised airport indicators are reported.

From the ANSP perspective, the analysis now focuses on the availability and effective utilization of downstream spare operational capacity during the CAEHO process. In particular, the following assessment quantifies the amount of downstream spare operational-capacity exposure associated with tactical delegation operations across adjacent sectors.

Let $\mathcal{R}$ denote the set of receiving downstream sectors. Let $O_s(t)$ denote the occupancy of sector s at time t , and let C_s denote the declared maximum capacity of sector s .

For each receiving sector $s \in \mathcal{R}$, the instantaneous downstream spare-capacity ratio is defined as:

$$S_s(t) = \frac{C_s - O_s(t)}{C_s} \quad (14)$$

where:

$$0 \leq S_s(t) \leq 1 \quad (15)$$

This quantity represents the fraction of unused operational capacity available in receiving sector s at time t .

The CAEHO assessment is performed over the temporal interval $T_{\text{CAEHO}} = [t_0, t_{\text{last}}]$, where t_0 denotes the triggering time of the CAEHO mechanism and t_{last} denotes the time at which the last delegated aircraft exits the original overloaded sector.

The cumulative downstream spare-capacity exposure available during the CAEHO process is then expressed as:

$$H_{\text{avail}} = \sum_{s \in \mathcal{R}} A_s \int_{T_{\text{CAEHO}}} S_s(t) dt \quad (16)$$

where A_s represents the equivalent operational ATCO resources associated with receiving sector s . In the present assessment, each active receiving sector is assumed to operate with one executive ATCO and one planner ATCO, i.e., $A_s = 2$.

Accordingly, H_{avail} represents a normalized cumulative measure of available downstream spare-capacity opportunity during CAEHO-feasible conditions.

Based on this formulation, the normalized downstream spare-capacity utilization efficiency indicator is defined as:

$$G_{\text{CAEHO}} = \frac{F^{\text{avoided}}}{H_{\text{avail}}} \quad (17)$$

where F^{avoided} denotes the total number of flights for which ATC-capacity regulation was avoided, as reported in Table 2. The resulting units are expressed as *flights·ATCO·hour*⁻¹.

Physically, the proposed indicator quantifies how effectively available downstream spare-capacity opportunity contributes to overload mitigation through CAEHO delegation.

The corresponding quantitative results are presented in Section 5.4.

4. Results

4.1. Immediate mitigation impact of the CAEHO mechanism

The following results analyze the immediate mitigation impact of the CAEHO mechanism in terms of operational performance indicators. Specifically, the analysis focuses on the reduction of delayed flights, the reduction of flights subject to regulation, and the decrease in total delay minutes. All simulations have been conducted for remaining dwell times of 300, 360, 420, and 480 s, and across both the base scenario ($\delta = 0$) and progressively stressed scenarios ($\delta = 1, 2, 3, 4$).

Table 2

CAEHO mitigation outcomes by stress level (δ) and remaining dwell time. Avoided values and percentages are computed relative to a common baseline without CAEHO activation.

δ	Remaining Dwell Time (s)	Avoided Delay Min	Avoided Reg. Flights	Avoided Delayed Flights	% Delay Min Avoided	% Reg. Flights Avoided	% Delayed Flights Avoided
0	300	35,246	7570	2004	47.57	51.75	48.44
0	360	36,499	7832	2095	49.26	53.54	50.64
0	420	39,538	8321	2302	53.37	56.88	55.64
0	480	39,858	8403	2327	53.80	57.44	56.25
1	300	19,411	4882	1214	26.20	33.37	29.34
1	360	32,069	6811	1799	43.28	46.56	43.49
1	420	35,563	7529	2030	48.00	51.47	49.07
1	480	38,602	8018	2237	52.10	54.81	54.07
2	300	13,667	2915	817	18.45	19.93	19.75
2	360	19,913	4605	1211	26.88	31.48	29.27
2	420	32,335	6890	1812	43.64	47.10	43.80
2	480	35,938	7383	2027	48.51	50.47	49.00
3	300	12,571	2681	741	16.97	18.33	17.91
3	360	13,560	2982	814	18.30	20.39	19.68
3	420	23,891	4232	1264	32.25	28.93	30.55
3	480	29,279	5177	1618	39.52	35.39	39.11
4	300	10,441	1968	583	14.09	13.45	14.09
4	360	12,778	2574	740	17.25	17.60	17.89
4	420	15,627	3128	908	21.09	21.38	21.95
4	480	15,627	3128	908	21.09	21.38	21.95

Table 2 summarizes the mitigation outcomes of the CAEHO mechanism across different stress levels ($\delta = 0$ to 4) and remaining dwell times (300–480 s). All scenarios are evaluated against a common baseline, corresponding to the observed capacity regulations without CAEHO activation, which resulted in a total of 74,089 delay minutes, 14,628 regulated flights, and 4137 delayed flights over the study period. The table therefore reports only the delay minutes, regulated flights, and delayed flights avoided through CAEHO activation, together with the corresponding percentages relative to the baseline. These indicators provide a direct measure of the immediate mitigation efficiency of CAEHO under increasing operational stress and expanding anticipatory time windows.

The results presented in Table 2 confirm that the CAEHO mechanism produces a significant mitigation effect across all scenarios analyzed. In the base configuration ($\delta = 0$), more than half of the total regulated flights and delay minutes are avoided, demonstrating the strong potential of early delegation to relieve sector congestion without altering the underlying traffic demand.

As the stress level increases, the mitigation efficiency progressively decreases, reflecting the reduced flexibility of the system under more saturated conditions. Even so, for moderate stress levels ($\delta = 1$ and $\delta = 2$), the mechanism still avoids between 40% and 50% of delay minutes and regulated flights, indicating that CAEHO remains effective under realistic operational perturbations.

At higher stress levels ($\delta = 3$ and $\delta = 4$), the mitigation capability declines sharply, with avoided delay minutes falling below 20% in the most stressed case. This behavior suggests a nonlinear degradation of system resilience, where overload peaks exceed the coordination capacity offered by the available dwell-time margins.

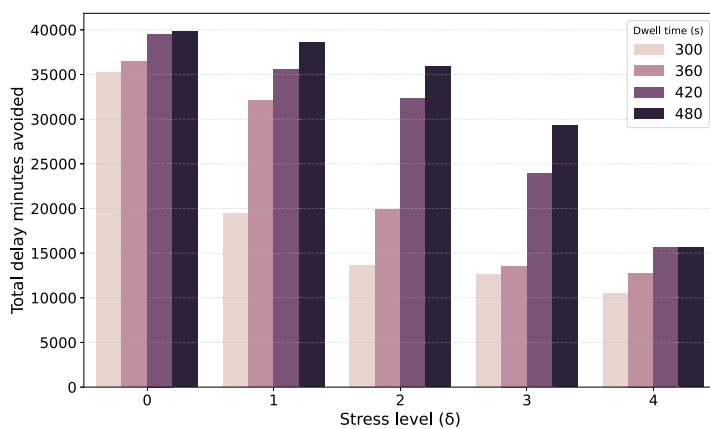
Finally, results across dwell-time configurations show that longer remaining dwell times consistently enhance CAEHO performance, as they extend the coordination window available for early delegation. However, beyond 420 s, the marginal benefit tends to stabilize, indicating diminishing returns from further extending the anticipatory window. This saturation effect is also observed under the highest stress level ($\delta = 4$), where increasing the remaining dwell time from 420 to 480 s does not lead to additional mitigation gains, suggesting that the system reaches an effective limit beyond which further anticipation does not translate into higher efficiency, as residual overload peaks may be mitigated but not sufficiently to prevent regulation activation.

Consistent patterns are observed in the histogram-based visualization shown in Fig. 8.

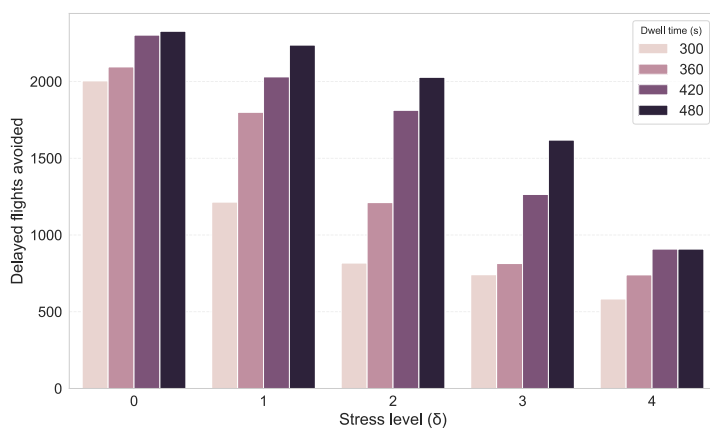
4.2. Temporal distribution of the regulations

Analyzing the temporal distribution of regulations throughout the day is essential, since the operational impact of a regulation extends beyond its immediate duration. A delay imposed in the early hours of the day may propagate through subsequent flight legs or rotations, amplifying its overall effect across the network. Conversely, a regulation occurring in the late afternoon or evening typically has a more localized impact, as most aircraft have fewer remaining operations within the same day. Consequently, identifying whether a regulation—or its avoidance through CAEHO or similar mechanisms—takes place in the morning or in the evening provides valuable insight into its cumulative benefit. Avoiding a morning regulation can yield far-reaching advantages, reducing propagated delays and improving the overall daily performance of the system.

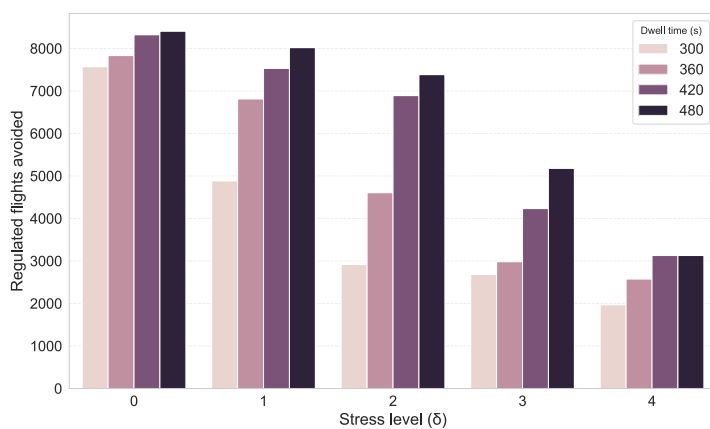
The temporal analysis of regulations reveals a pronounced asymmetry in how delay-generating events are distributed across the day. Under baseline conditions, the cumulative share of regulation-driven delay minutes (Fig. 9a) grows rapidly during the morning hours and reaches approximately half of its daily total by around 11:00. By 14:00, close to 80% of all regulated delay



(a) Histogram of total saved delay minutes.

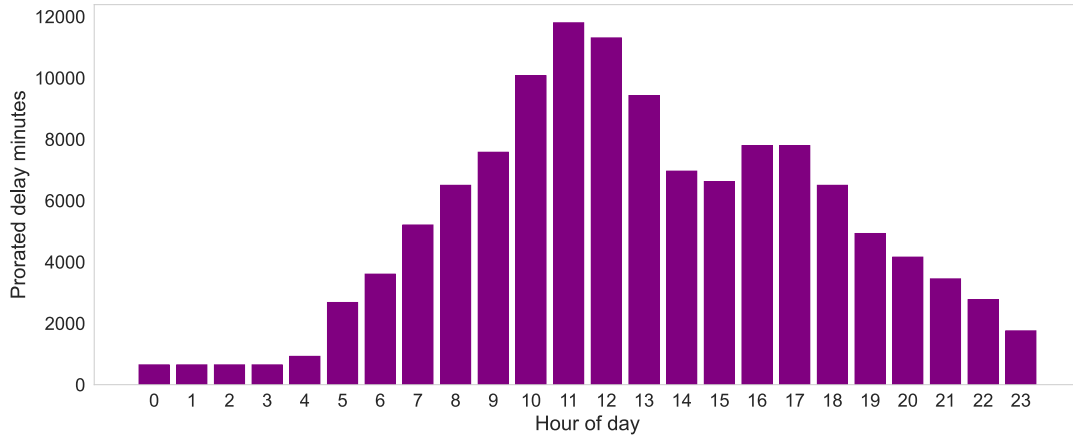


(b) Histogram of saved delayed flights.

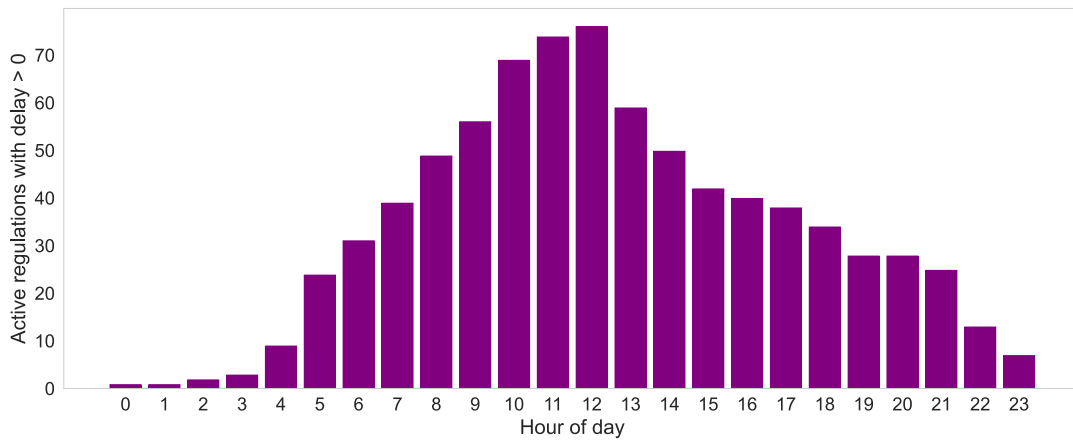


(c) Histogram of saved regulated flights.

Fig. 8. Main impact of the CAEHO mechanism according to different stress levels and remaining dwell times.



(a) Histogram of delays per hour.



(b) Histogram of active regulations producing effective delays.

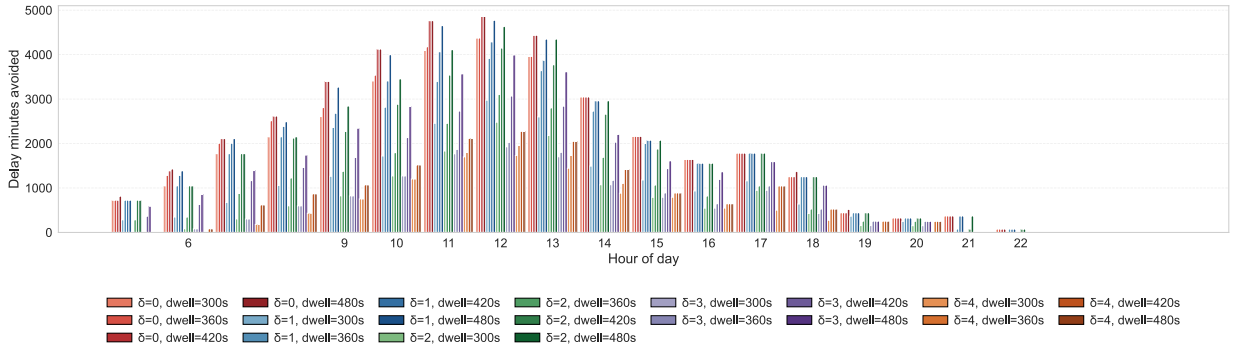
Fig. 9. Baseline impact histograms.

minutes have already been generated, while the remaining fraction accumulates slowly during the afternoon. After approximately 16:00 LT, the cumulative curve stabilises, indicating that the occurrence of new ATC-capacity regulations becomes sparse and that their incremental contribution to the total delay is minor. This front-loaded profile demonstrates that the European air traffic network is most constrained during the first half of the operational day. Similar behaviour is observed in the distribution of delayed flights throughout the day (Fig. 9b).

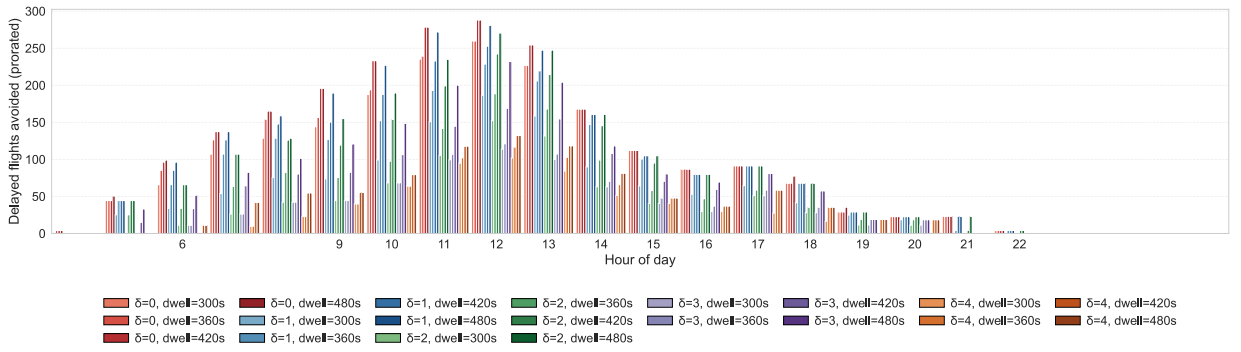
Beyond identifying when regulations and delays occur, it is equally important to determine where and under which conditions the CAEHO mechanism has been most effective in mitigating disruptions. Since the mechanism is evaluated under multiple combinations of stress levels and dwell-time configurations, the resulting figures present the complete range of possible outcomes. Each scenario corresponds to a specific pair of parameters (δ, T) , where δ represents the incremental traffic stress applied to the sector and T the minimum dwell-time threshold defining early-handover eligibility. Fig. 10a, b, and c illustrate how the mechanism performs across this parameter space, showing the avoided delay minutes, delayed flights, and regulated flights, respectively.

These results demonstrate that the CAEHO mechanism systematically reduces the operational impact of ATC-capacity regulations by shortening or neutralising the most critical regulation episodes. The effect is particularly significant during the early hours of the day, when the cumulative concentration of regulations is highest and even small improvements yield cascading benefits on subsequent rotations.

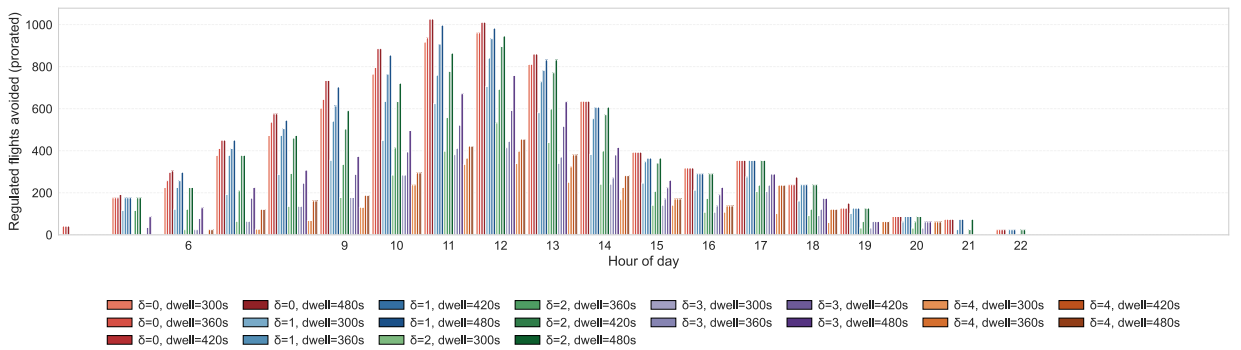
The cumulative temporal analysis of avoided delay minutes further supports this interpretation. Across all combinations of stress level and dwell-time threshold, the cumulative distribution maintains a remarkably consistent shape: approximately 50% of the total avoided delay minutes are achieved by around 12:00, 80% between 15:00 and 16:00, and 90% by approximately 17:00. This invariance across parameters indicates that the temporal window in which CAEHO is most effective is structurally determined by the



(a) Avoided delay minutes per hour.



(b) Avoided delayed flights per hour.



(c) Avoided regulated flights per hour.

Fig. 10. Hourly distribution of the avoided impact produced by the CAEHO mechanism.

network's intrinsic regulation dynamics rather than by the specific parameter configuration. By concentrating its effectiveness during the morning and early midday hours, CAEHO acts at the core of the daily propagation cycle, preventing the amplification of early congestion and contributing to a more stable and resilient operational network.

5. Impact assessment

This section translates the operational mitigation indicators reported in Section 4 into stakeholder impacts following the methodology described in Sections 3.5–3.7. The monetised layer values only the delay that is directly attributable to ATFCM regulations due to sector overload. Airline benefits are valued using Eurocontrol's strategic en-route delay cost coefficient, and passenger benefits are valued using the AVoT reported in Table 1. In line with the literature (Delgado et al., 2021; Gurtner and Bolić, 2023), airport and ANSP impacts are not monetised and are instead interpreted using operational proxies and qualitative mechanisms.

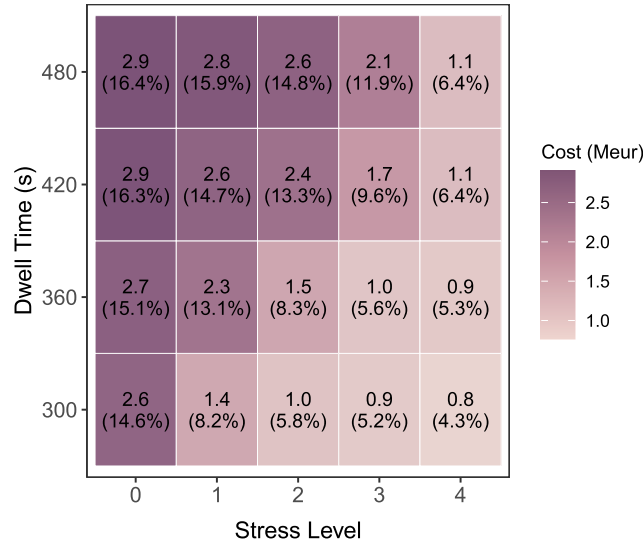


Fig. 11. Monetised total cost avoided of ATFCM regulation delay across stress levels and dwell-time thresholds for airlines (M€ per day and % of reduction).

5.1. Monetised impacts for airlines and passengers

Figs. 11 and 12 summarise the monetised avoided cost of ATFCM regulation delay (M€ per day) across stress levels and dwell-time thresholds, reported separately for airlines and passengers, respectively. In the base stress scenario ($\delta = 0$), the avoided total cost for both users ranges from 5.0 M€ per day at $T = 300$ s to 5.6 M€ at $T = 480$ s. The increase in benefits with longer dwell-time thresholds is consistent with the operational results in Table 2: longer eligibility windows enable more effective early delegation, but the marginal gains diminish beyond $T = 420$ s.

Under moderate stress, CAEHO continues to deliver substantial monetised benefits. For instance, at $\delta = 2$, the avoided cost reaches 5.0 M€ per day for $T = 480$ s, indicating that the mechanism remains effective under realistic perturbations. Under high stress ($\delta = 4$), benefits decrease to the range 1.5–2.2 M€ per day because the network becomes strongly capacity-constrained and fewer overload peaks can be mitigated through delegation alone.

A consistent finding across scenarios is that airline and passenger benefits are of similar order of magnitude. This occurs because Eurocontrol's average airline strategic delay valuation (82.95 €/min) is comparable to passenger time valuation once scaled by passenger volumes: with typical aircraft in the sample carrying around 160–170 passengers, passenger time cost per minute is of the same magnitude as airline time cost per minute. This strengthens the policy relevance of a stakeholder framing, as both major user groups experience material gains from avoiding regulation-induced delay.

5.2. Fleet-equivalent interpretation of avoided delay

To provide a strategic interpretation of the time savings beyond monetary valuation, we express avoided ATFCM regulation delay as a fleet-equivalent utilisation proxy using the method in Section 3.6. This metric is informative for policy because it translates dispersed delay minutes into an intuitive capacity-equivalent quantity, while remaining conservative and not claiming an immediate fleet reduction.

In the base scenario ($\delta = 0$, $T = 360$ s), CAEHO avoids 36,499 min of ATFCM regulation delay across the ECAC network, corresponding to 608 aircraft-hours. When scaled by observed daily airborne utilisation (about 17.4 airborne hours per deployed aircraft-day), this represents approximately 35 fleet-equivalent aircraft, or about 0.55% of the network peak airborne fleet (measured in the sample). At airline level, the implied fleet-equivalent savings are of order 1–7 aircraft for the most affected carriers (Table 3), corresponding to roughly 0.4–2.1% of their deployed ECAC fleets. The value of this result is not that an airline can remove exactly F_a aircraft in the short run, but that the mechanism reduces the amount of aircraft-time that must be absorbed through buffers, reserve capacity, or reduced utilisation when regulations are used as the default stabiliser.

Fig. 13 shows that CAEHO yields positive fleet-equivalent savings for all airlines and scenarios (fleet measured in the sample). Savings generally increase with regulation time, while the effect of stress level is smaller and less systematic. The largest absolute reductions are concentrated in the most recurrent carriers, especially RYR, whereas the percentage savings are modest and typically remain in the low double-digit range.

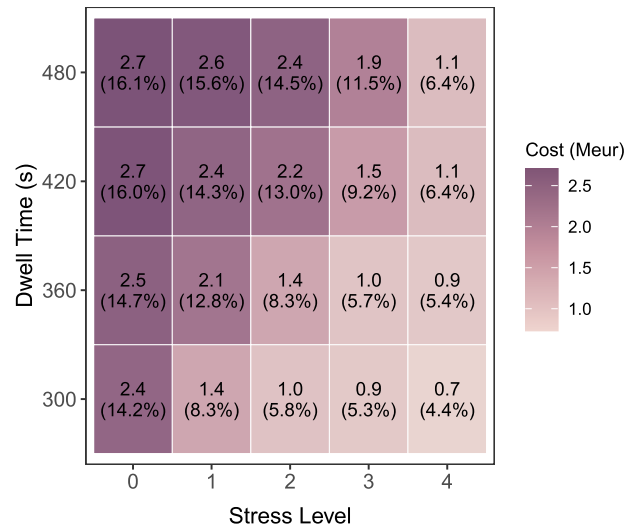


Fig. 12. Monetised total cost avoided of ATFCM regulation delay across stress levels and dwell-time thresholds for passengers (M€ per day and % of reduction).

Table 3

Fleet-equivalent time savings from avoided ATFCM regulation delay by airline (stress $\delta = 0$, $T = 360$ s).

Concept	RYR	EZY	ITY	EJU	EWG	EXS	NJE	BAW	AFR	VOE
Peak airborne (ac.)	545	165	77	126	104	114	55	163	182	44
Avoided delay (min)	6407	1902	1373	1445	1276	939	500	798	764	740
Aircraft-hours (h)	106.8	31.7	22.9	24.1	21.3	15.7	8.3	13.3	12.7	12.3
Fleet-equiv. (ac.)	6.13	1.91	1.60	1.49	1.32	0.93	0.92	0.82	0.80	0.71
Share of fleet (%)	1.13	1.16	2.08	1.19	1.27	0.82	1.68	0.51	0.44	1.62

5.3. Distributional effects across airlines

Beyond aggregate welfare, the distribution of benefits across operators matters for regulatory feasibility. Fig. 14 shows the avoided airline delay cost by carrier in the base stress scenario ($\delta = 0$, $T = 360$ s). Fig. 15 shows the corresponding values for all scenarios and the 12 recurring airlines, using EUROCONTROL's strategic en-route delay coefficient. The pattern is clearly skewed: a small number of large carriers achieve avoided costs in the hundreds of thousands of euros, while the majority of carriers exhibit much smaller gains. The ranking drops sharply after the first few operators, producing a long tail of airlines with avoided costs in the order of tens of thousands of euros. This concentration primarily reflects exposure—airlines with high flight volumes and stronger presence in the regulated parts of the network naturally accrue more avoided delay—rather than preferential treatment, since CAEHO acts on sector-feasibility and delegation opportunities rather than on airline-specific priorities.

The fleet-equivalent utilisation proxy introduced in Section 3.6 provides a complementary interpretation in capacity terms. While absolute monetary benefits scale with the volume of operations, scaling avoided delay by each airline's observed airborne utilisation yields a more comparable measure of strategic relief. For the most affected carriers, the implied fleet-equivalent savings are of order 1–7 aircraft on the analysed day (Fig. 13), which is best interpreted as reduced buffer and reserve requirements rather than as a literal short-run fleet reduction.

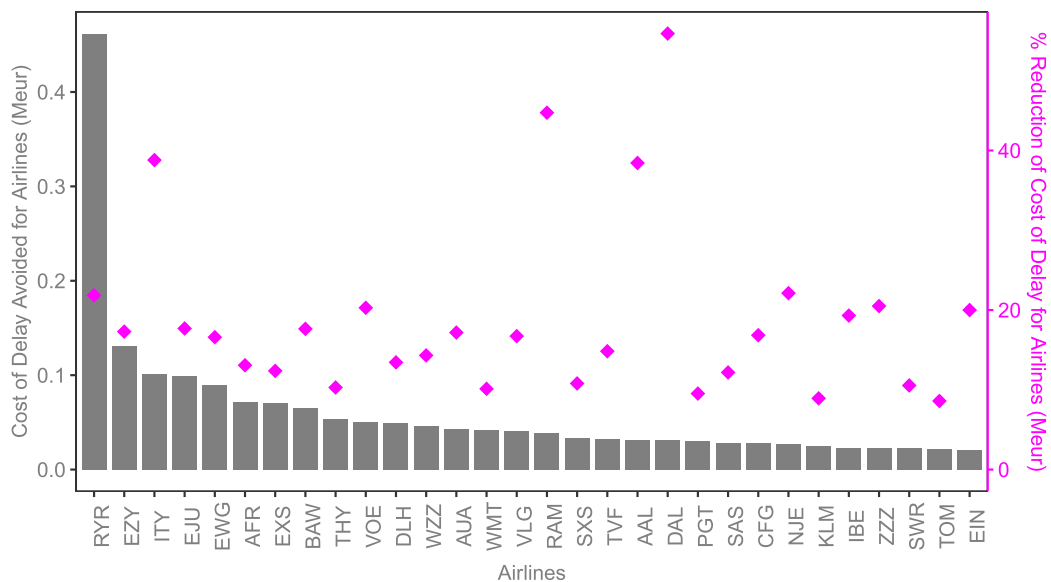
From a governance perspective, the observed skewness underlines the need for transparency and auditable decision rules. As with other adaptive congestion-management policies, acceptance depends not only on aggregate efficiency gains but also on whether stakeholders perceive the allocation of benefits and burdens as fair. For SES implementation, this motivates routine reporting of distributional indicators alongside aggregate cost savings, and clear communication of the criteria under which early delegation decisions are triggered.

5.4. Airport and ANSP impacts represented through proxies

Airports and ANSPs are central stakeholders in ATFCM regulation, but their impacts are not directly monetised in this study. As noted by Delgado et al. (2021) and reinforced by Gurtner and Bolić (2023), cost-of-delay estimation is fundamentally airline-centric and extending monetary coefficients to other actors is methodologically fragile. Moreover, although fewer ATFCM regulations may reduce operational strain for airports and ANSPs, they do not automatically translate into proportional short-run cost reductions.

Airline	300					360					420					480				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
RJR	6.0 (1.1)	3.4 (0.6)	2.8 (0.5)	2.7 (0.5)	2.1 (0.4)	6.1 (1.1)	5.6 (1.0)	3.8 (0.7)	2.8 (0.5)	2.7 (0.5)	6.6 (1.2)	6.1 (1.1)	5.7 (1.0)	4.7 (0.9)	3.3 (0.6)	6.7 (1.2)	6.6 (1.2)	6.2 (1.1)	5.5 (1.0)	3.3 (0.6)
EZY	1.9 (1.1)	1.2 (0.7)	0.9 (0.5)	0.9 (0.5)	0.8 (0.5)	1.9 (1.2)	1.6 (1.0)	1.0 (0.6)	1.0 (0.6)	0.9 (0.6)	2.2 (1.3)	1.9 (1.1)	1.7 (1.0)	1.1 (0.7)	1.0 (0.6)	2.2 (1.3)	2.2 (1.3)	2.0 (1.2)	1.4 (0.8)	1.0 (0.6)
EJU	1.4 (1.1)	0.6 (0.5)	0.5 (0.4)	0.4 (0.3)	0.4 (0.3)	1.5 (1.2)	1.4 (1.1)	0.8 (0.6)	0.4 (0.3)	0.4 (0.3)	1.6 (1.3)	1.5 (1.2)	1.4 (1.1)	1.1 (0.9)	0.6 (0.5)	1.7 (1.3)	1.6 (1.3)	1.6 (1.2)	1.4 (1.1)	0.6 (0.5)
BAW	0.8 (0.5)	0.5 (0.3)	0.4 (0.2)	0.3 (0.2)	0.3 (0.2)	0.8 (0.5)	0.8 (0.5)	0.4 (0.3)	0.3 (0.2)	0.3 (0.2)	1.0 (0.6)	0.8 (0.5)	0.8 (0.5)	0.5 (0.3)	0.3 (0.2)	1.0 (0.6)	1.0 (0.6)	0.9 (0.6)	0.7 (0.4)	0.3 (0.2)
EWG	1.3 (1.2)	0.8 (0.7)	0.4 (0.4)	0.2 (0.2)	0.2 (0.2)	1.3 (1.3)	1.2 (1.1)	0.7 (0.6)	0.3 (0.3)	0.3 (0.3)	1.3 (1.3)	1.3 (1.2)	1.1 (1.0)	0.6 (0.6)	0.4 (0.3)	1.3 (1.3)	1.3 (1.2)	1.2 (1.2)	0.7 (0.6)	0.4 (0.3)
EXS	0.8 (0.7)	0.5 (0.4)	0.3 (0.3)	0.3 (0.2)	0.3 (0.2)	0.9 (0.8)	0.6 (0.6)	0.4 (0.4)	0.3 (0.3)	0.3 (0.2)	1.4 (1.2)	0.9 (0.8)	0.8 (0.7)	0.4 (0.3)	0.3 (0.3)	1.4 (1.2)	1.3 (1.1)	1.2 (1.0)	0.9 (0.8)	0.3 (0.3)
ITY	1.6 (2.1)	0.3 (0.3)	0.2 (0.3)	0.2 (0.3)	0.2 (0.3)	1.6 (2.1)	1.5 (2.0)	0.6 (0.7)	0.2 (0.3)	0.2 (0.3)	1.6 (2.1)	1.6 (2.1)	1.5 (2.0)	1.4 (1.9)	0.5 (0.7)	1.6 (2.1)	1.6 (2.1)	1.5 (2.0)	1.5 (1.9)	0.5 (0.7)
VOE	0.7 (1.6)	0.3 (0.6)	0.3 (0.6)	0.2 (0.5)	0.2 (0.5)	0.7 (1.6)	0.6 (1.5)	0.4 (0.8)	0.2 (0.5)	0.2 (0.5)	0.8 (1.8)	0.7 (1.6)	0.6 (1.5)	0.6 (1.3)	0.3 (0.8)	0.8 (1.8)	0.8 (1.8)	0.7 (1.7)	0.7 (1.5)	0.3 (0.8)
NJE	0.9 (1.6)	0.3 (0.5)	0.2 (0.4)	0.2 (0.4)	0.2 (0.3)	0.9 (1.7)	0.9 (1.6)	0.4 (0.8)	0.2 (0.4)	0.2 (0.3)	1.0 (1.8)	0.9 (1.7)	0.9 (1.6)	0.8 (1.5)	0.3 (0.6)	1.0 (1.8)	1.0 (1.8)	1.0 (1.7)	0.9 (1.7)	0.3 (0.6)
AFR	0.8 (0.4)	0.4 (0.2)	0.4 (0.2)	0.2 (0.1)	0.1 (0.1)	0.8 (0.4)	0.7 (0.4)	0.4 (0.2)	0.2 (0.1)	0.1 (0.1)	0.9 (0.5)	0.8 (0.4)	0.7 (0.4)	0.4 (0.2)	0.2 (0.1)	0.9 (0.5)	0.9 (0.5)	0.7 (0.4)	0.6 (0.3)	0.2 (0.1)
VLG	0.5 (0.5)	0.4 (0.4)	0.3 (0.3)	0.3 (0.3)	0.2 (0.2)	0.6 (0.5)	0.5 (0.5)	0.5 (0.5)	0.4 (0.4)	0.4 (0.3)	0.7 (0.6)	0.6 (0.5)	0.5 (0.5)	0.5 (0.4)	0.5 (0.4)	0.7 (0.6)	0.7 (0.6)	0.6 (0.6)	0.6 (0.5)	0.5 (0.4)
RAM	0.5 (0.9)	0.5 (0.9)	0.4 (0.8)	0.4 (0.7)	0.2 (0.4)	0.6 (1.1)	0.5 (0.9)	0.4 (0.8)	0.4 (0.7)	0.4 (0.7)	0.6 (1.1)	0.6 (1.1)	0.4 (0.8)	0.4 (0.7)	0.4 (0.7)	0.6 (1.2)	0.6 (1.1)	0.5 (0.9)	0.4 (0.8)	0.4 (0.7)

Fig. 13. Fleet-equivalent savings for top 12 recurring airlines and percentage of reduction (%).

Fig. 14. Avoided airline delay cost by carrier in the base scenario ($\delta = 0$, $T = 360$ s), valued using eurocontrol strategic en-route delay cost.

Airline	300					360					420					480				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
RJR	4.5 (21.2)	2.6 (12.1)	2.1 (10.0)	2.1 (9.8)	1.6 (7.6)	4.6 (21.8)	4.2 (20.0)	2.9 (13.5)	2.1 (10.0)	2.0 (9.6)	5.0 (23.6)	4.6 (21.6)	4.3 (20.1)	3.5 (16.7)	2.5 (11.7)	5.1 (23.9)	4.9 (23.4)	4.7 (22.0)	4.1 (19.5)	2.5 (11.7)
EZY	1.3 (16.9)	0.8 (10.4)	0.6 (7.9)	0.6 (7.9)	0.6 (7.4)	1.3 (17.3)	1.1 (14.5)	0.7 (9.0)	0.6 (8.6)	0.6 (8.3)	1.5 (20.1)	1.3 (16.9)	1.2 (15.6)	0.8 (10.2)	0.6 (8.6)	1.5 (20.1)	1.5 (19.6)	1.4 (18.5)	1.0 (12.7)	0.6 (8.6)
EJU	1.0 (17.0)	0.4 (7.2)	0.3 (5.6)	0.3 (5.0)	0.2 (4.3)	1.0 (17.7)	1.0 (16.9)	0.5 (8.9)	0.3 (5.1)	0.3 (4.9)	1.1 (19.4)	1.0 (17.3)	0.9 (16.2)	0.8 (13.4)	0.4 (6.9)	1.1 (19.9)	1.1 (19.1)	1.0 (18.6)	0.9 (16.1)	0.4 (6.9)
EXS	0.6 (11.0)	0.4 (6.7)	0.2 (4.0)	0.2 (3.8)	0.2 (3.4)	0.7 (12.4)	0.5 (8.3)	0.3 (5.8)	0.2 (4.1)	0.2 (3.8)	1.0 (17.9)	0.7 (11.6)	0.6 (10.6)	0.3 (4.9)	0.2 (4.1)	1.0 (17.9)	1.0 (17.1)	0.9 (15.4)	0.6 (11.1)	0.2 (4.1)
BAW	0.7 (17.6)	0.4 (11.4)	0.3 (8.6)	0.2 (5.1)	0.2 (5.0)	0.7 (17.6)	0.6 (17.2)	0.4 (10.1)	0.2 (6.4)	0.2 (6.3)	0.8 (20.6)	0.7 (17.6)	0.6 (17.2)	0.4 (9.5)	0.2 (6.4)	0.8 (20.6)	0.8 (20.6)	0.7 (19.5)	0.6 (15.0)	0.2 (6.4)
EWG	0.9 (16.0)	0.5 (9.6)	0.3 (4.8)	0.2 (3.0)	0.2 (2.9)	0.9 (16.6)	0.8 (14.9)	0.5 (8.4)	0.2 (4.3)	0.2 (4.2)	0.9 (16.6)	0.8 (15.7)	0.7 (13.5)	0.4 (7.3)	0.2 (4.5)	0.9 (16.6)	0.8 (15.8)	0.8 (15.2)	0.4 (8.2)	0.2 (4.5)
AFR	0.7 (12.4)	0.5 (8.2)	0.4 (7.4)	0.2 (4.1)	0.1 (1.9)	0.7 (12.6)	0.6 (11.4)	0.5 (8.1)	0.2 (4.1)	0.1 (1.9)	0.8 (13.5)	0.7 (12.6)	0.7 (11.6)	0.4 (6.9)	0.1 (2.4)	0.8 (13.5)	0.8 (13.5)	0.7 (11.9)	0.6 (10.6)	0.1 (2.4)
ITY	1.0 (38.8)	0.2 (6.2)	0.1 (5.4)	0.1 (5.4)	0.1 (5.4)	1.0 (38.8)	1.0 (37.3)	0.3 (13.2)	0.1 (5.4)	0.1 (5.4)	1.0 (39.0)	1.0 (38.8)	1.0 (36.7)	0.9 (34.6)	0.3 (12.4)	1.0 (39.0)	1.0 (39.0)	1.0 (37.3)	0.9 (35.4)	0.3 (12.4)
VOE	0.5 (20.3)	0.2 (7.4)	0.2 (7.2)	0.2 (6.5)	0.2 (6.5)	0.5 (20.3)	0.5 (18.2)	0.3 (10.5)	0.2 (6.5)	0.2 (6.5)	0.6 (23.0)	0.5 (20.3)	0.5 (18.2)	0.4 (15.9)	0.2 (9.6)	0.6 (23.0)	0.6 (23.0)	0.5 (20.9)	0.5 (18.9)	0.2 (9.6)
THY	0.5 (10.0)	0.4 (7.0)	0.2 (3.2)	0.2 (3.0)	0.2 (3.0)	0.5 (10.3)	0.5 (9.2)	0.3 (6.4)	0.2 (3.0)	0.2 (3.0)	0.5 (10.3)	0.5 (10.0)	0.5 (9.2)	0.3 (5.0)	0.2 (4.1)	0.5 (10.3)	0.5 (10.0)	0.5 (9.9)	0.4 (7.2)	0.2 (4.1)
VLG	0.4 (14.8)	0.3 (12.1)	0.2 (9.4)	0.2 (9.4)	0.1 (4.9)	0.4 (16.7)	0.4 (14.5)	0.3 (14.3)	0.3 (11.2)	0.2 (10.1)	0.5 (19.1)	0.4 (16.7)	0.3 (14.3)	0.3 (13.4)	0.3 (13.4)	0.5 (19.2)	0.5 (19.1)	0.4 (16.9)	0.4 (16.5)	0.3 (13.4)
RAM	0.3 (38.5)	0.3 (37.1)	0.3 (34.8)	0.3 (29.9)	0.1 (17.2)	0.4 (44.7)	0.3 (38.5)	0.3 (36.5)	0.3 (29.9)	0.3 (29.9)	0.4 (46.7)	0.4 (44.7)	0.3 (36.5)	0.3 (31.3)	0.3 (31.3)	0.4 (49.2)	0.4 (46.7)	0.4 (40.5)	0.3 (33.6)	0.3 (31.3)

Fig. 15. Airline delay cost avoided by carrier across all the scenarios and percentage of reduction (%).

In the case of ANSPs, any such savings would depend on local staffing rules, roster flexibility, overtime arrangements, and sector opening practices, which are outside the scope of the present analysis.

For airports, the expected benefits of fewer ATFCM regulations relate primarily to improved predictability of departure and arrival streams, reduced short-notice gate and stand conflicts, and smoother turnaround planning. Since robust and transferable airport-specific delay-cost coefficients are not available, these impacts are not monetised in this study. Instead, they are quantified through operational proxy indicators that measure the amount of regulation-induced disruption removed from each airport's departure and arrival streams.

For each flight whose ATFCM regulation delay is avoided by CAEHO, one avoided regulation-impact incidence is assigned to the departure airport and one to the arrival airport. The corresponding avoided delay minutes are also attributed to both sides of the airport interface. This produces airport-level indicators of avoided departure-side exposure, avoided arrival-side exposure, and total avoided airport exposure, measured both in incidences and in delay minutes. Avoided departure-side exposure reflects fewer flights whose airport departure process is disrupted by regulation-induced ground delay, whereas avoided arrival-side exposure reflects improved predictability in inbound flows and downstream airport processes.

These airport-level indicators should therefore be interpreted as operational predictability proxies rather than as direct monetised airport cost savings. They complement the aggregate reduction in regulated flights and delayed flights reported in Table 2, as well as the temporal distribution of avoided delay discussed in Section 4.2, by showing how avoided regulation-induced disruption is spatially distributed across departure and arrival airports.

Figs. 16–18 report this spatial distribution of airport-level avoided regulation exposure. Fig. 16 focuses on the reference scenario ($\delta = 0$, $T = 360$ s), assigning avoided regulation-delay minutes to the departure and arrival airports of each affected flight. Fig. 17 complements this duration-based view by reporting avoided regulation-impact incidences, thereby distinguishing the frequency of affected airport streams from the magnitude of avoided delay exposure. Fig. 18 extends the analysis across all stress and dwell-time scenarios, showing whether the same airports remain recurrently exposed under different CAEHO operating conditions.

For ANSPs, avoided regulations imply fewer or shorter episodes in which sector demand exceeds declared capacity. Although declared capacity itself remains unchanged, reducing overload peaks is operationally relevant for workload stability, sector configuration continuity, and reduced reliance on reactive flow restrictions. It may also lessen the need for short-notice staffing adjustments,

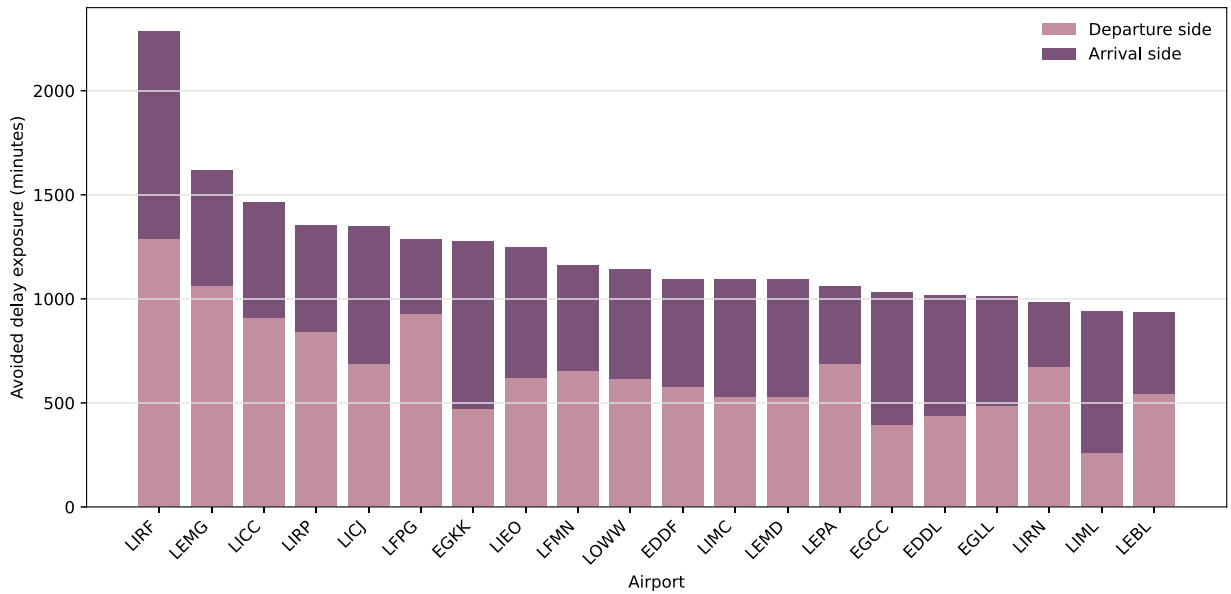


Fig. 16. Airport-level avoided regulation-delay exposure in the reference scenario ($\delta = 0$, $T = 360$ s). Values are attributed to both the departure and arrival airport of each flight whose ATFCM regulation delay is avoided. The indicator represents operational exposure to avoided disruption and should not be interpreted as monetised airport cost savings.

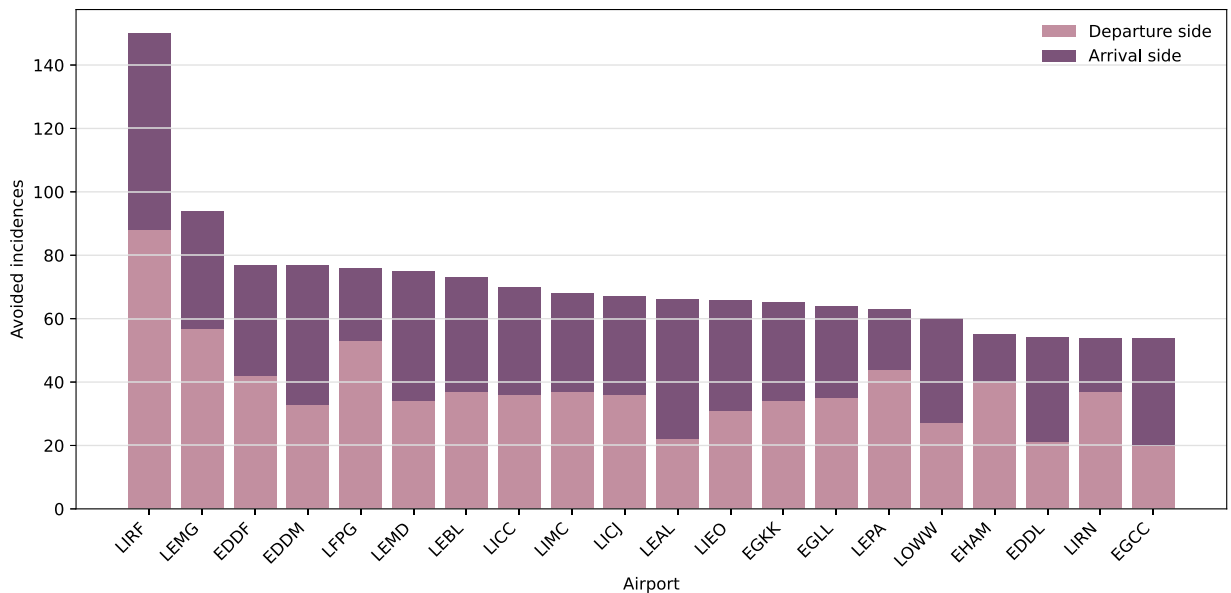


Fig. 17. Airport-level avoided regulation-impact incidences in the reference scenario ($\delta = 0$, $T = 360$ s). Each avoided affected flight contributes one incidence to its departure airport and one incidence to its arrival airport, distinguishing the frequency of departure-side and arrival-side exposure.

duty extensions, or overtime in some operational contexts; however, these effects are highly ANSP-specific and cannot be robustly monetised without detailed institutional and roster-level data.

Accordingly, ANSP-related impacts are assessed through a combination of proxy overload-mitigation indicators and a complementary downstream spare-capacity utilization assessment. Proxy indicators include avoided regulations, avoided delayed flights, avoided delay minutes, and robustness patterns across stress levels δ , which characterize the degradation of CAEHO effectiveness under progressively saturated traffic conditions.

Applying the downstream spare-capacity utilization framework introduced in Section 3.8 to the ECAC-wide case-study scenarios produced the cumulative downstream spare-capacity exposure values shown in Table 4.

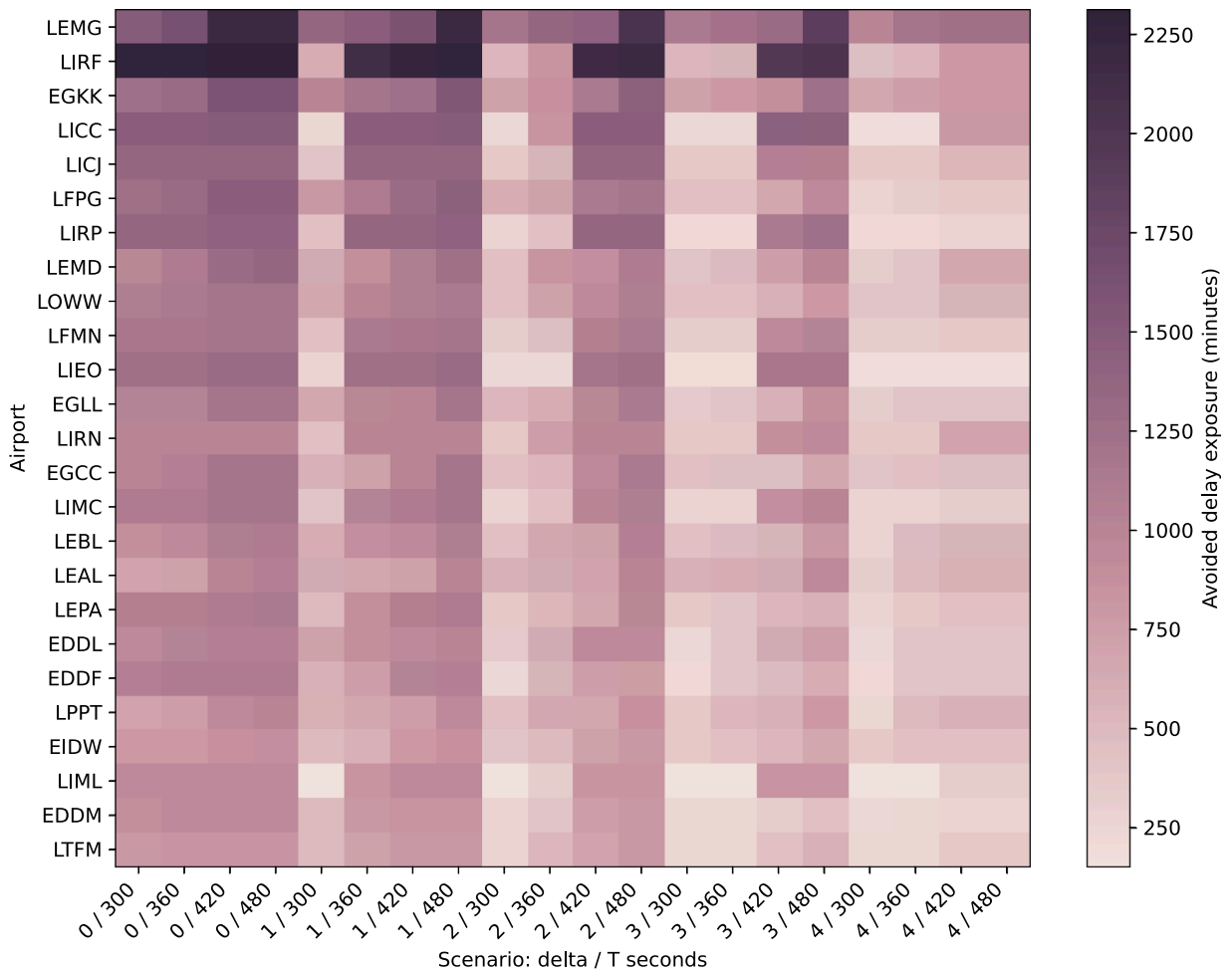


Fig. 18. Airport-level avoided regulation-delay exposure across stress levels and remaining dwell-time thresholds. Rows show the airports with the largest total avoided delay exposure, and columns represent CAEHO scenarios defined by δ/T . Values correspond to total avoided delay exposure minutes attributed to departure and arrival streams.

Table 4

Estimated cumulative downstream spare-capacity exposure available for CAEHO delegation under different remaining dwell-time windows.

Remaining Dwell Time (s)	H_{avail} (ATCO-hours)
300	26.24
360	30.67
420	35.08
480	39.43

As expected, increasing the CAEHO temporal horizon progressively enlarges the cumulative downstream spare-capacity exposure available for delegation, since larger remaining dwell-time windows extend the temporal interval during which downstream sectors may absorb delegated traffic.

Using the avoided delayed-flight results presented in Table 2, the corresponding normalized downstream spare-capacity utilization efficiency indicator can be estimated for the baseline stress scenario ($\delta = 0$). The resulting values are:

- 300 s: ≈ 76.4 flights·ATCO-hour⁻¹,
- 360 s: ≈ 68.3 flights·ATCO-hour⁻¹,
- 420 s: ≈ 65.6 flights·ATCO-hour⁻¹,
- 480 s: ≈ 59.0 flights·ATCO-hour⁻¹.

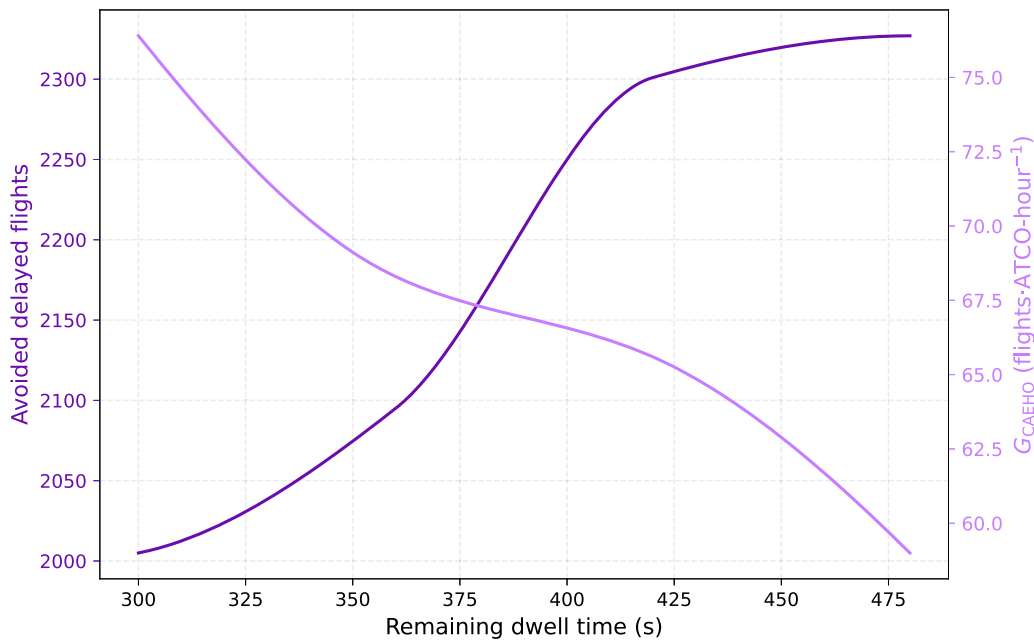


Fig. 19. Trade-off between avoided delayed flights and normalized downstream spare-capacity utilization efficiency under increasing remaining dwell-time windows.

Table 5
Stakeholder impact matrix used in the assessment.

Stakeholder	Impact channel	Measurement in this study
Airlines	Avoided regulation-induced en-route delay; utilisation	Monetised: avoided delay minutes $\times$ Eurocontrol strategic en-route cost coefficient (Table 1)
Passengers	Avoided travel-time loss due to regulations	Monetised: avoided passenger-minutes $\times$ AVoT (Table 1), passenger exposure estimated from seats $\times$ load factor (Section 3.7)
Airports	Operational predictability; gate/stand stability	Not monetised: proxy interpretation using changes in regulated/delayed flights and temporal distribution of avoided delay (Section 4.2)
ANSPs	Workload redistribution; utilization of available downstream operational capacity	Not monetised: operational proxy indicator based on avoided delayed flights and effective downstream spare-capacity utilization across stress levels and CAEHO windows (Section 5.4)

The results reveal a diminishing-return relationship between downstream spare-capacity opportunity and the corresponding overload-mitigation gains achieved through CAEHO.

Fig. 19 shows that increasing the remaining dwell-time window increases the number of avoided delayed flights, while simultaneously reducing the normalized downstream spare-capacity utilization efficiency indicator G_{CAEHO} .

This behavior suggests a diminishing-return relationship between increasing downstream spare-capacity opportunity and the resulting overload-mitigation gains achieved through CAEHO delegation.

Furthermore, increasing stress levels (δ) reduce the number of avoidable delayed flights while the surrounding downstream spare-capacity opportunity remains bounded by the operational network configuration. As a result, heavily stressed traffic scenarios tend to exhibit progressively lower downstream spare-capacity utilization efficiency.

It should be emphasized that H_{avail} does not represent additional effective ATCO working hours or direct institutional cost efficiency. Instead, it represents a normalized cumulative measure of downstream spare-capacity opportunity available during CAEHO-feasible conditions.

Accordingly, the proposed formulation should be interpreted as an ANSP-oriented operational-performance indicator related to downstream airspace-capacity utilization and tactical workload redistribution during CAEHO-feasible conditions, rather than as a formal SESAR CEF2 productivity metric (SESAR Joint Undertaking, 2019).

5.5. Summary stakeholder impact matrix

Table 5 summarises how the impact assessment treats each stakeholder group. Airlines and passengers are monetised using standard unit values, while airports and ANSPs are captured through proxy indicators consistent with the methodological limitations reported in the literature.

6. Policy implications

The results have direct implications for the Single European Sky (SES) agenda and for current reliance on ATFCM regulations as the default mechanism to preserve capacity feasibility under sector overload. ATFCM regulations are necessary from a safety perspective when demand exceeds declared capacity, but they also function as an administrative time-penalty mechanism that transfers congestion costs to airspace users. The evidence in Sections 4 and 5 indicates that a substantial share of regulation-induced en-route delay can be avoided through earlier coordination and workload redistribution, without modifying traffic demand or declared sector capacities.

From an efficiency perspective, the monetised impacts are material. In the base stress scenario, the avoided cost of regulation-induced delay reaches approximately 5.0–5.6 M€ per day depending on the dwell-time threshold, with diminishing marginal gains beyond $T = 420$ s. Under moderate stress, benefits remain large, while under extreme saturation the mechanism delivers smaller but still non-negligible gains. This pattern supports a key policy interpretation: algorithmic balancing mechanisms are best understood as a complement that reduces reliance on regulations in typical constrained operations, rather than as a substitute for structural capacity measures under extreme demand or staffing shortfalls.

From an equity and acceptability perspective, the distribution of benefits matters. The airline-level allocation of avoided delay costs is concentrated among a subset of carriers with high exposure to regulated flows. This is expected, but it implies that implementation must address transparency and perceived fairness, particularly if stakeholders suspect that adaptive mechanisms systematically advantage certain operators, business models, or regions. Lessons from surface transport control (e.g., ramp metering) suggest that acceptance depends on explicit objectives, auditable decision rules, and clear communication of trade-offs. For SES implementation, this implies that algorithmic balancing should be governed by transparent criteria and accompanied by stakeholder-facing evaluation protocols.

Finally, the analysis supports adopting mixed appraisal protocols in ATM policy evaluation. For airlines and passengers, standardised unit values enable conservative monetisation grounded in Eurocontrol inputs. For airports and ANSPs, the literature indicates that actor-specific monetary valuation is not robust, and the appropriate approach is to report proxy indicators linked to predictability and workload stability. This hybrid structure aligns with multi-actor regulatory impact assessment practice and provides a practical route to integrate operational performance evidence into policy debate without overstating the precision of monetisation where it is not warranted.

7. Conclusion and further research

This paper examines the use of ATFCM regulations to manage sector-level ATC-capacity constraints and associated demand-capacity imbalances in the ECAC airspace. While necessary to preserve safety and capacity feasibility, such regulations can unintentionally generate systemic inefficiencies by grounding aircraft and imposing regulation-induced delays that propagate across daily airline schedules. Using a stakeholder-oriented appraisal framework that distinguishes monetised impacts for airlines and passengers from non-monetised operational proxy indicators for airports and ANSPs, the study compared the current regulatory baseline with an algorithmic demand-capacity balancing strategy inspired by the CAEHO mechanism, which is applied upon detection of a sector overload to eliminate the exceedance and thereby avoid the deployment of ATC-capacity regulations by transferring control and communication of a cluster of eligible aircraft to adjacent sectors with available spare capacity.

The results indicate that a substantial proportion of regulation-induced delay can be avoided while fully respecting declared sector capacity and without modifying underlying traffic demand. Under baseline operating conditions, the mechanism prevents a substantial fraction of regulation-driven delay minutes and of flights that would otherwise have been subject to ATC-capacity regulations, with effectiveness depending on both the available remaining dwell time and the severity of sector overloads. This finding suggests that part of observed ATC-capacity regulation reflects reliance on rigid allocation rules and limited tactical coordination rather than unavoidable capacity scarcity. The stress analysis further indicates that the mechanism is most effective under typical constrained conditions and less effective under extreme saturation, confirming that algorithmic balancing should be understood as a complementary instrument that limits reliance on regulation rather than a substitute for structural capacity or staffing measures.

Beyond aggregate efficiency, the analysis shows that regulatory change redistributes benefits and costs unevenly across stakeholders. Monetised benefits are concentrated among airlines with high exposure to ATC-capacity regulation, while many operators experience smaller gains, reflecting differences in traffic exposure rather than preferential treatment. This uneven distribution has direct governance implications. Experience with adaptive congestion-management policies indicates that acceptance depends on transparent objectives, auditable decision rules, and explicit communication of distributional effects. For European ATM, this implies that algorithmic balancing mechanisms must be embedded within governance frameworks that address equity and perceived fairness alongside efficiency.

From a policy perspective, the avoided impacts are economically meaningful for both airlines and passengers. Using valuation assumptions consistent with established European ATM performance assessments, the results indicate that reducing regulation-induced delay can generate material welfare gains under typical operating conditions. These findings support the role of algorithmic balancing mechanisms as effective tactical tools to limit the use of ATC-capacity regulations within the current European ATM framework.

A notable result is that the benefits for airlines and passengers are of comparable magnitude. While airline gains arise from avoided strategic delay costs, passenger benefits accumulate across large numbers of travellers experiencing improved schedule reliability.

This underscores the importance of a stakeholder-based perspective: reducing ATC-capacity regulation delivers value not only by lowering airline operating costs, but also by providing tangible reliability improvements for passengers.

From an institutional perspective, CAEHO operates strictly within the airspace configuration defined under ASM and does not modify sector geometry, boundary topology, or configuration deployment. The structural partition of airspace remains unchanged. Its intervention takes place at the operational interface where ATFCM manages demand relative to declared capacity. By enabling temporary redistribution of control responsibility across predefined sector interfaces under explicit capacity safeguards, CAEHO introduces additional flexibility into how demand-capacity imbalances are resolved without triggering structural reconfiguration. In this sense, the mechanism complements ASM-defined structural capacity while directly affecting the need for ATC-capacity regulations within ATFCM. The present analysis therefore evaluates CAEHO primarily through its interaction with ATFCM regulation, as regulation constitutes the observable policy instrument under consideration, while recognising that its operational relevance emerges from the coordinated interaction between ASM-defined capacity and ATFCM demand management.

Institutional and regulatory feasibility emerges as a central consideration. While the results show that adaptive demand-capacity balancing can reduce reliance on ATC-capacity regulations, implementation may be constrained by regulatory inertia, heterogeneous data availability, and resistance from established actors. These factors affect adoption independently of technical performance. Consequently, effective deployment requires governance arrangements that ensure transparency of algorithmic decisions, clearly defined triggering criteria, and accountability structures compatible with the evolving European institutional framework.

Several directions for further research follow from these findings. First, external validity could be strengthened by extending the analysis to multiple representative days and seasons, as regulation patterns and spare-capacity availability vary over time. Second, future work could explore how different levels of automation and decision-support maturity affect the coordination burden associated with early delegation, recognising that coordination workload is itself shaped by governance choices rather than being an exogenous constraint. Third, distributional analysis could be extended beyond airline-level impacts to route, region, and airport-level patterns that are directly relevant for policy design and stakeholder acceptance. Finally, environmental effects should be quantified explicitly rather than inferred, as the net impact on fuel burn and emissions depends on behavioural responses and operational substitutions that require dedicated modelling.

CRedit authorship contribution statement

Alfons Borràs: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **César Trapote-Barreira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Strategic delay cost by aircraft type

Aircraft-specific strategic delay costs were assigned using the closest EUROCONTROL reference type available in Table 16.4 (Eurocontrol, 2024). Exact matches were used when available. Otherwise, aircraft were mapped to the nearest proxy based on family, propulsion type, size, and operating role. Thus, narrow-body aircraft were linked to the closest Airbus or Boeing short-haul or medium-haul reference, long-haul aircraft to A332 or B744 type proxies, and residual regional or light aircraft to DH8D or E190 depending on whether they were operationally closer to turboprop/commuter or regional/small-jet service. This replaces the use of a single average strategic delay cost with a simple aircraft-specific approximation consistent with the EUROCONTROL framework.

Table A.1

Aircraft-specific strategic delay cost used in the study.

Proxy (Eurocontrol, 2024)	Cost (€/min)	Aircraft in dataset
A319	67.70	A319, BCS1
A320	69.08	A19N, A20N, A21N, A320, BCS3
A321	81.77	A321
A332	142.93	A306, A310, A332, A333, A338, A339, A359, A35K, B772, B77L, B77W, B788, B789, B78X, C10T, C17
AT72	25.15	AT72, AT73, AT75, AT76
B734	65.13	B733, B734
B735	58.40	B735, B736
B738	72.27	B38M, B39M, B737, B738, B739
B744	216.78	A388, B744, B748
B752	83.35	B752, B753
B763	123.35	B763, B764
DH8D	32.27	B350, BE20, BE9L, C30J, CN35, DA42, DH8D, M20P, P180, PA46, PC12, SR20, SW4, TBM9
E190	54.45	BE40, C25A, C25B, C25C, C25M, C510, C525, C55B, C56X, C680, C68A, C700, C750, CL30, CL35, CL60, CRJ2, CRJ9, CRJX, E135, E145, E190, E195, E290, E295, E35L, E50P, E545, E550, E55P, E75L, E75S, F2TH, F900, FA10, FA6X, FA7X, FA8X, GA5C, GA6C, GA7C, GALX, GL5T, GL7T, GLEX, GLF4, GLF5, GLF6, H25B, HDJT, K35R, LJ31, LJ40, LJ45, LJ60, LJ75, PC24, PRM1, SF50

Note: Strategic en-route delay costs are taken from Table 16.4 of the EUROCONTROL Standard Inputs (Eurocontrol, 2024). Exact matches were used when available; otherwise, the closest reference aircraft was used as proxy.

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