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Master Thesis

Development of a Mathematical Model for STAM Measures Optimal Application

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Abstract

This thesis addresses the challenge of managing demand and capacity in the air transportation system, specifically focusing on Very Short-Term ATFCM Measures (VSTAM) to relieve congestion in en-route airspace. The aim is to develop and validate a mathematical model that identifies the optimal VSTAM when there is an imbalance between demand and capacity in a given airspace within the near future. The research is conducted within the framework of DCB tools to validate the efficient use of airspace capacity of the SESAR3 IR1 HARMONIC project. The document is structured into five chapters, covering the current methodology for Air Traffic Flow and Capacity Management, a review of state-of-the-art concepts for resolving demand and capacity imbalances, the context in which the proposed model is to be validated —both concerning the airspace design and the timeframe of application—, the proposed mathematical model for classifying VSTAM measures and flights, and the results obtained along with their detailed analysis.

The mathematical model developed in the thesis focuses on identifying the cost function associated with the application of level-capping or rerouting measures. This cost function classifies the flights associated with a given demand-capacity imbalance considering their contribution to the sector complexity as well as the impact of possible rerouting or level-capping on their trajectory. The thesis also includes a simulation with historical demand data to validate the mathematical model, applying the cost function to solve demand-capacity imbalance situations. The results obtained from the simulation are presented and analyzed in the final chapter. Overall, the thesis provides a comprehensive exploration of the challenges and potential solutions for managing demand and capacity in the air transportation system, offering a valuable contribution to the field of Air Traffic Flow and Capacity Management.

Resumen

Esta tesis aborda el desafío de gestionar la demanda y la capacidad en el sistema de transporte aéreo, centrándose específicamente en las Very Short-Term ATFCM Measures (VSTAM) para aliviar la congestión en el espacio aéreo en ruta. El objetivo es desarrollar y validar un modelo matemático que identifique el VSTAM óptimo cuando existe un desequilibrio entre la demanda y la capacidad en un espacio aéreo dado en un futuro cercano. La investigación se lleva a cabo dentro del marco de las herramientas DCB para validar el uso eficiente de la capacidad del espacio aéreo del proyecto SESAR3 IR1 HARMONIC. El documento está estructurado en cinco capítulos, que abarcan la metodología actual para la Gestión del Flujo de Tráfico Aéreo y la Capacidad, una revisión de los conceptos de vanguardia para resolver desequilibrios de demanda y capacidad, el contexto en el que se validará el modelo propuesto, tanto en lo que respecta al diseño del espacio aéreo como al marco temporal de aplicación, el modelo matemático propuesto para clasificar las medidas VSTAM y los vuelos, y los resultados obtenidos junto con su análisis detallado.

El modelo matemático desarrollado en la tesis se centra en identificar la función de coste asociada con la aplicación de medidas de level-capping o rerouting. Esta función de coste clasifica los vuelos asociados con un desequilibrio entre la demanda y la capacidad considerando su contribución a la complejidad del sector, así como el impacto de posibles reroutings o level-cappings en su trayectoria. La tesis también incluye una simulación con datos históricos de demanda para validar el modelo matemático, aplicando la función de coste para resolver situaciones de desequilibrio entre la demanda y la capacidad. Los resultados obtenidos de la simulación se presentan y analizan en el capítulo final. En general, la tesis proporciona una exploración exhaustiva de los desafíos y soluciones potenciales para gestionar la demanda y la capacidad en el sistema de transporte aéreo, ofreciendo una valiosa contribución al campo de la Gestión del Flujo de Tráfico Aéreo y la Capacidad.

Contribution

HARMONIC has received funding from the SESAR 3 Joint Undertaking (JU) under grant agreement No 101114675. The JU receives support from the European Union's Horizon Europe research and innovation programme and the SESAR 3 JU members other than the Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or SESAR 3 Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Acronyms

Acronym	Meaning
AB	Airspace Block
ACC	Area Control Centre
ADP	ATFCM Daily Plan
AOR	Area of Responsibility
ASM	Airspace Management
ATC	Air Traffic Control
ATCo	Air Traffic Controller
AU	Airspace User
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATOT	Actual Take-Off Time
CASA	Computer-Assisted Slot Allocation
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
COTTON	Capacity OptimisaTion in Trajectory-based OperatioNs
CTOT	Controlled Take-Off Time
DAC	Dynamic Airspace Configuration
DCB	Demand and Capacity Balance
EFTMS	Enhanced Tactical Flow Management System
ES	Elementary Sector
ETOT	Estimated Take-Off Time
FMP	Flow Management Position
IFR	Instrumental Flight Rules
INAP	Integrated Network Management and Extended ATC Planning
KPI	Key Performance Indicator
LTM	Local Traffic Manager
MDI	Minimum Departure Intervals
MIT	Miles-in-trail
MUAC	Maastricht Upper Area Control Centre
NM	Network Manager
NOP	Network Operations Portal
RFL	Reference Flight Level
SAB	Shareable Airspace Block
SID	Standard Instrumental Departure

STAM	Short-Term ATFCM Measures
STAR	Standard Arrival Route
TBO	Trajectory-Based Operations
TMA	Terminal Maneuver Area
VFR	Visual Flight Rules
VSAB	Vertical Shareable Airspace Block
VSTAM	Very Short-Term ATFCM Measures

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Introduction

The aviation industry has been grappling with the issue of capacity constraints and congestion in the airspace for a long time —only in the Spanish airspace, 1.1M minutes of delay were reported during the last year. The main problem that underlies the frequently low reliability and high associated costs of modern air transport systems is the relationship between capacity and demand that currently exists in some areas of the en-route airspace. Airlines and their passengers currently incur significant costs due to capacity limitations, congestion that results, and poor schedule reliability. It is not anticipated that these issues will be resolved in the near or medium term by significant capacity increases.

To address this problem, different demand and capacity management measures have been proposed. These measures aim to improve the reliability and performance of air transportation services by managing demand and capacity in US and European air transportation systems. Currently, there are two main currents of study to tackle the DCB challenge. The first one is related to the modification of sectorisation, which entails changing the shape of the airspace sectors in a dynamic way to adapt them to the air traffic demand. The main benefit of this concept, the Dynamic Airspace Configuration, is that sectors can be more easily adapted to air traffic demand, but the current idea of knowing in advance the shape and flow of the sectors for control purposes disappears. The second stream of research focuses on moving from the ATFM paradigm based on regulations —which are not necessarily optimal— and CASA, to a model in which flights are assigned to individual measures by solving a global slot allocation problem. One such measure is the implementation of Short-Term ATFCM Measures (STAM). These measures are designed to relieve congestion at those points of imbalance (hotspots) between the capacity and demand of en-route airspace.

The objective of this master's thesis is to develop and validate a mathematical model that identifies the optimal Short-Term ATFCM Measures when there is an imbalance between demand and capacity in a given airspace within the near future. This model has been developed within the framework of DCB tools for validating the efficient use of airspace capacity of the SESAR3 IR1 HARMONIC project.

The mathematical model in question focuses on identifying the cost function associated with the application of level-capping or rerouting measures. This cost function classifies the flights associated with a given demand-capacity imbalance considering their contribution to the sector complexity as well as the impact of a possible rerouting or level-capping to their trajectory.

In order to validate the developed mathematical model, a simulation has been carried out with historical demand data applying the cost function to solve demand-capacity imbalance situations in which the real-life solution was the imposition of a ground delay.

The document is structured in five chapters. Chapter 1 outlines the current methodology for the Air Traffic Flow and Capacity Management according to the Network Manager ATFCM Operations Manual. Chapter 2 reviews the current state-of-the-art for the different concepts regarding the resolution of demand and capacity imbalances, both from the capacity measures and demand measures points of view. Chapter 3 describes the design of the airspace in which this project is located and describes the problem to be solved by this thesis. Chapter 4 proposes the mathematical model to classify the different VSTAM measures and flights within a given overloaded sector and defines the scenario in which it is to be validated. Finally, Chapter 5 shows the results obtained as well as their detailed analysis.

1 Current Operating Method

This chapter describes the current methodology used to manage the demand and capacity balancing in the European Air Traffic Management domain. This methodology has been extracted from the Eurocontrol Network Manager ATFCM Operations Manual [1].

According to the ICAO, the Air Traffic Management domain consists of three main parts:

- Airspace Management (ASM)
- Air Traffic Flow and Capacity Management (ATFCM)
- Air Traffic Control (ATC)

Airspace, like any other commodity, is a valuable and finite resource that requires careful management, especially during periods of high demand. Airspace Management (ASM) involves planning, defining sectors, and managing airspace to meet user needs efficiently and fairly. However, due to economic activity and increased demand, the available air traffic control capacity requires a mechanism to avoid overloads and optimise airspace use through dynamic flow management.

Air Traffic Flow and Capacity Management (ATFCM) aims to match airspace and aerodrome capacity with traffic demand, and when capacity is exhausted, it adjusts the demand to fit the maximum available capacity. This adjustment may involve allocating specific departure times (slots) to individual aircraft to mitigate bottlenecks and minimise safety risks. This process involves continuous communication and information exchange with all European air traffic control units and aircraft operators.

1.1 Air Traffic Flow and Capacity Management

The objective of the Air Traffic Flow and Capacity Management (ATFCM) is to prevent overloading of certain areas of the airspace while ensuring that its capacity is maximised, which is essential in a congested and active airspace, such as the European one.

The main roles in ATFCM consist of the Network Manager (NM) and the flow management positions (FMP) assigned by area control centres (ACC). These entities participate in a collaborative decision-making process, utilising various supporting tools such as OPTICON, which aids in selecting the sector configuration. Both the NM and FMPs have the ability to conduct ATFCM simulations to assess a series of capacity constraints. These simulations evaluate factors such as the total delay generated, delay distribution, and individual delay generated by each capacity constraint. The aim is to identify the most effective measure to implement, with consensus from other stakeholders.

Given the importance of time in implementing ATFCM demand/capacity balance (DCB) measures and the inherent unpredictability in air traffic demand, ATFCM tasks are divided into three temporal phases within a continuous time horizon.

- Strategic flow management: This process takes place up to seven days before the day of operation (D), with the main focus on collecting data to identify early major demand/capacity imbalances, such as shows, major sporting events, and military exercises. Regarding imbalances, the NM generates the network operations plan (NOP) to optimise the available airspace capacity. Measures simulated to generate the NOP include level capping scenarios, diverting flows to offload traffic from certain areas, and alternative routing scenarios.

- Pre-tactical flow management: This process is implemented from six days prior to the operational day (D-6) to D-1, to analyse the traffic demand for the day of the operation, propose the necessary adjustments to the NOP, harmonise the demand and capacity, and ensure the cost-efficient use of available capacity.

  The main ATFCM measures at the pre-tactical phase that can be planned at D-1 are: sector management (sector configuration, number of sectors, collapsing/splitting sectors), balancing arrival/departure capacity, flight list assessment (flights of minor workload), negociating extra capacity (monitoring values, occupancy counts), civil-military coordination, reducing traffic complexity, holding the pattern and regulating the demand.

  The agreed-upon measures between NM and FMPs are formalised in the ATFCM daily plan, which covers a 24-hour period for each day, starting as a draft on D-2 and finalised on D-1. During tactical operations, the ADP is further modified as the uncertainty of traffic demand is reduced.

- Tactical flow management: This process takes place on the operation day (D) to analyse, in real time, events that affect the ATFCM daily plan; it proposes the necessary plan modifications to solve the demand/capacity imbalances. Although there are several causes that may require these adjustments (i.e. staffing problems, significant meteorological phenomena, crises...), the most reported cause is *ATC capacity*, which includes any unexpected limitation related to air infrastructure.

  On the operation day, if detected imbalances cannot be mitigated by measures to increase capacity due to technical staff, or set-up time limitations, ATFCM capacity measures focus on traffic regulations. These regulations include the allocation of individual aircraft departure times, rerouting, and alternative flight profiles through different mechanisms, such as network cherry-picking regulations, constrained airborne capacities, minimum departure intervals (MDIs), or miles-in-trail (MIT). The FMP is responsible for the implementation of specific regulations; it provides the NM with details on the sector configurations and activations, traffic volumes, their monitoring values, and information about events that will impact capacity at an aerodrome or ACC.

1.2 Collaborative Decision Making (CDM)

Collaborative Decision Making (CDM) is a process that allows for decisions to be made by those best positioned to do so, based on comprehensive and up-to-date information. It ensures all stakeholders have the opportunity to influence the decision, leading to performance objectives being met and flights being optimised in real-time.

The implementation of Air Traffic Flow and Capacity Management (ATFCM) measures within an Area of Responsibility (AoR) is usually preceded by a CDM process. This process allows organisations to continuously update each other on events from the strategic level to real-time. The CDM process is inclusive, and transparent, and builds trust between the parties involved.

The ATFCM CDM process is designed to ensure that stakeholders, service providers, and airspace users can discuss airspace, capacity/demand, and flight efficiency issues. The discussions lead to a consensus view and solution, implying an official commitment of each participant.

In the Strategic phase, the focus is on analysing major events and anticipated capacity shortfalls for individual Area Control Centers (ACCs) / airports and the network. The result is a set of agreed ATFCM measures/solutions to be considered for implementation in the pre-tactical and tactical phases.

ATFCM measures considered in pre-tactical / tactical phases could be extracted from pre-agreed strategic ATFCM measures or envisaged as ad-hoc measures to respond to a new situation triggered by a change either in traffic demand or Air Traffic Control (ATC) system capacity. The output of these daily conferences is the ATFCM daily plan (ADP), which is constantly updated during the day of operations through further CDM processes.

Participants should include involved Network Management (NM) staff, Air Navigation Service Providers (ANSPs), Airspace Users (AUs), affected military authorities, and airport authorities. If an agreement cannot be reached, the implementation of a specific regulation is the responsibility of the Flow Management Position (FMP), with a monitoring and eventual escalation process to higher management envisaged if such a situation endures.

The final decision on the regulation implementation is for the FMP, but the details of the regulation itself should be coordinated with the NM. The implementation of a Network measure affecting the area of responsibility of multiple FMPs remains the responsibility of the NM.

1.3 ATFCM solutions to capacity shortfalls

To resolve capacity shortfalls and improve network capacity management, various ATFCM solutions are considered. These solutions aim to optimise the utilisation of available capacity, use other available capacities, and regulate the demand. They are thoroughly evaluated before implementation.

When overloads are detected, the CDM process is initiated, and different ATFCM solutions are considered between the NM and the respective Flow Management Position (FMP). These solutions include sector management, balancing arrival/departure capacity, flight list assessment, negotiating extra capacity, ATFCM/Airspace Management (ASM) coordination, reducing traffic complexity, and implementing holding patterns.

Other solutions aim to shift traffic demand into areas where capacity is available. These include rerouting, flight level management, advancing traffic, and FMP tactical ATFCM measures.

Regulating the demand involves imposing constraints on traffic. This consists of real-time optimisation of capacity/demand across Europe, and delay management where aircraft are affected by a regulation. This aims to offer alternatives and minimise the delay. Flights taking place on that day receive the benefit of ATFCM, which includes the allocation of individual aircraft departure times, reroutings to avoid bottlenecks, and alternative flight profiles to maximise efficiency. The implementation of regulations, network cherry-pick regulations, FMP tactical ATFCM measures, and constraining airborne capacity are also part of this process.

Fig. 1 represents an overview of the solutions that the Network manager considers for ATFCM.

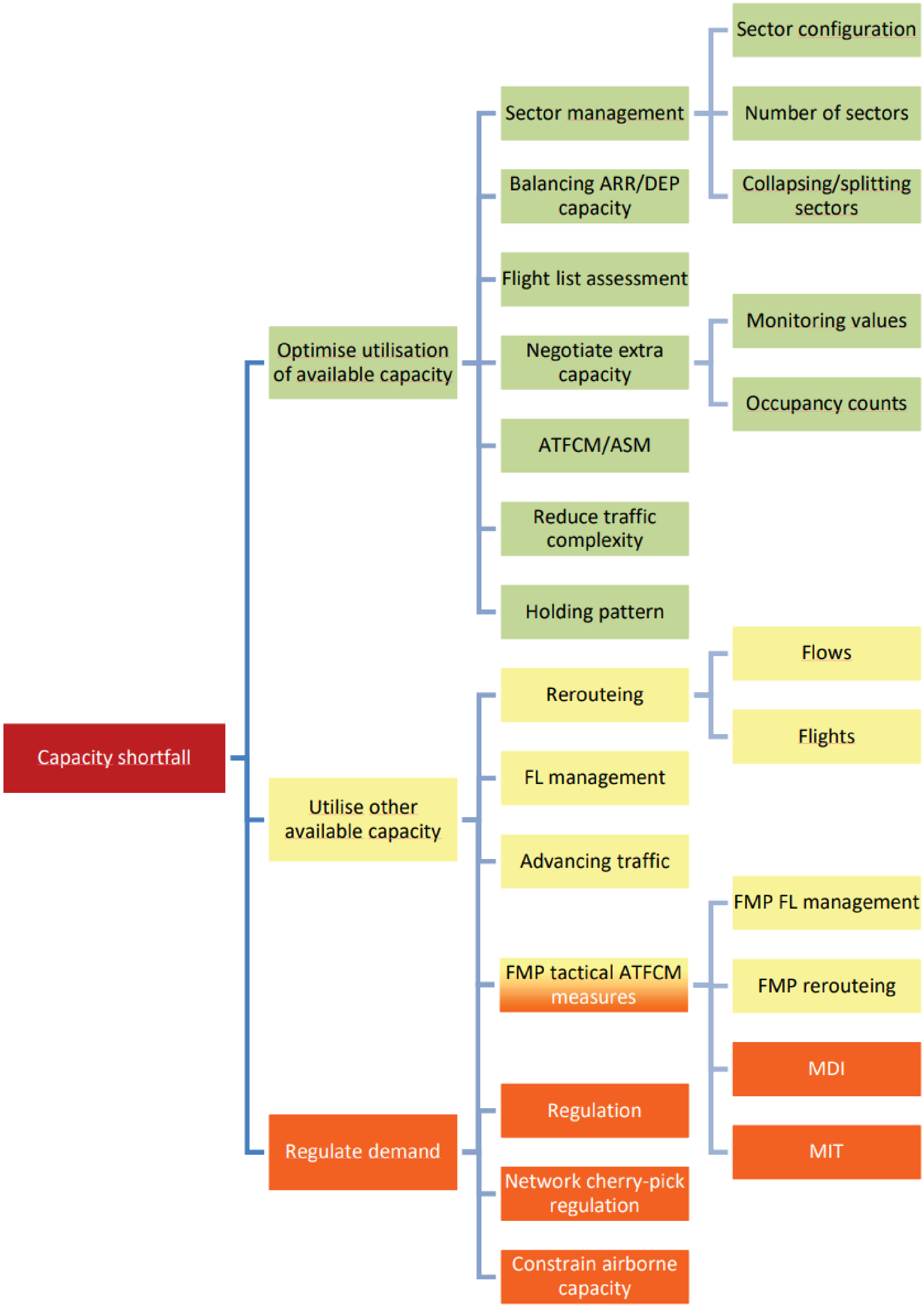


Figure 1: ATFCM Solutions to capacity shortfalls

1.4 STAMs

The DCB service, implemented by ATFCM, is based primarily on planned traffic as the basis for its operations. In Europe, the central flow management unit (CFMU) oversees the enhanced tactical flow management system (EFTMS), which monitors the current situation. To detect control sector overloads and propose appropriate regulations, the computer-assisted slot allocation (CASA) system is used. CASA offers two potential degrees of freedom: the ability to postpone take-offs and rerouting options.

On the day of operation, the DCB service comes into play to manage real-time imbalances that often arise due to discrepancies between planned and actual traffic. It serves as a mechanism for addressing these situations promptly and effectively. To maintain network stability and address any residual issues of limited magnitude, several key STAMs have been implemented. These measures involve making slight refinements to flights in both the execution phase and ground operations.

1.4.1 Types of STAMs

In this section, a series of the main STAMs are listed and described.

- Capacity management: to enhance capacity, one of the main STAM actions is the "Airspace Volume Configuration" service. This service enables dynamic capacity tuning through short-notice configuration changes. By leveraging the available resources, weather prediction, and incoming traffic flow, this service facilitates some responsive capacity adjustments.

- Tactical rerouting: ATCos have the authority to issue instructions, to redirect traffic away from congested sectors in real time, effectively alleviating saturation. Additionally, at the pre-flight level, the NM can suggest alternative routes to flights experiencing network delays, ensuring smoother flow throughout the airspace system.

- Level capping: this approach involves implementing flight-level limitations to redirect excessive flights from heavily burdened sectors to those with lighter traffic loads. The dDCB service facilitates the application of level capping, either at the individual flight level or as a flow-level adjustment. However, it is essential to inform the airspace users beforehand to ensure that they are aware of and can comply with the necessary adjustments before takeoff.

- Application of Minimum Departure Intervals: the dDCB service is instrumental in managing on-ground aircraft by implementing departure time intervals, which are assigned and overseen by the ATC tower. This service plays a vital role as one of the primary actions within the STAMs to reduce the workload of ATCos in TMA sectors. By strategically spacing out departure times, the dDCB service helps optimise the aircraft flow and reduces congestion in TMAs, ensuring a more efficient and manageable workload for ATCos.

- Miles-in-trail: en-route radar ATCos can activate a service that addresses separation minima infringements among aircraft to maintain the same speed or Mach number, controllers can effectively prevent these infringements. This service, which is categorised as a dDCB measure, plays a significant role in reducing the workload of ATCos.

- SID STAM: the ATC tower can make a slight adjustment to the planned standard instrumental departure route (SID), as a means to alleviate congestion in overloaded departure sectors. By implementing this change, the sector's capacity can be preserved, eliminating the need for ground regulations that could otherwise reduce capacity. This proactive approach ensures a more efficient flow of departures, optimising airspace utilisation and minimising disruptions. By using this method, the ATC tower effectively manages traffic volume and maintains operational capacity without resorting to ground regulations.

- Slot swapping: This STAM service plays a crucial role in assisting the ATFCM by identifying, assessing, and facilitating slot swapping for eligible flights. The aim is to minimise the impact of delays on airspace user operations. When a grounded aircraft anticipates challenges in completing its turnaround within the designated time frame, this service provides an opportunity to exchange its slot with another airspace user through a cooperative process involving the NM. By enabling this slot swapping, the service helps optimise the utilisation of available resources and reduce disruptions caused by delays.

There is only one automated method currently used to adjust traffic demand and alleviate congestion in air traffic sectors, which is the Computer-Assisted Slot Allocation (CASA). CASA allocates ground delay based on a First-Planned First-Served mechanism. The most common measure in Europe involves limiting the rate at which aircraft enter congested traffic volumes during specific periods, and activating regulations as needed. Flights subject to these regulations are issued a ground delay by the CASA system to ensure maximum entry rates in corresponding traffic volumes are not exceeded. Notably, CASA is a heuristic algorithm, not an optimization procedure, but is considered equitable by airspace users as it applies the same rules to all flights.

Flow managers across Europe, in collaboration with the Network Manager, decide when and where to apply regulations to resolve overloads in their areas of responsibility. Due to the complex interactions between active regulations in the network, the global delay is primarily governed by human judgment to resolve local problems. While humans can efficiently handle simple scenarios with moderate overloads, their performance is expected to deteriorate in critical scenarios, such as severe weather —reducing airspace capacity— or large-scale industrial actions.

2 Literature Review

Some authors have attempted to develop different models to solve the demand and capacity balancing problem, both from the capacity and demand perspectives, joint and separate. This chapter presents the state-of-the-art for solving this issue, both from the Dynamic Airspace Configuration (DAC) and demand measures optimisation points of view.

2.1 Dynamic Airspace Configuration (DAC)

In the past, Airspace Configuration Management and DCB were carried out in almost complete isolation within different timeframes, leading to system inefficiencies. The SESAR programme introduced the concept of Dynamic Airspace Configuration (DAC) and extended the Digital INAP concept as part of an integrated DCB process. The integration of DAC into an overall process with 4D constraints to balance capacity with demand up to the execution phase reflects the aim of seeing DAC as a part of the overall DCB solution.

DAC aims to identify the best configuration to manage demand in the most effective manner possible by utilising the resources at hand, whilst minimising any negative impact on Airspace Users through DCB measures and a corresponding CDM process. Expanding the number of configuration options allows for a better fit between available capacity and demand, increasing airspace capacity for both military and civilian users.

This new capability offers significant flexibility to respond to change in an intelligent and integrated way to resolve imbalances, especially when combined with the ability to operate within a timeframe up to execution. Collaboration to identify the optimal solution is embedded in the process to ensure compatibility across the network management tiers of local/sub-regional/regional levels.

Since DAC is a fairly new concept that has yet to be implemented –except for some flexible airspace structures implemented in France and the MUAC area–, various SESAR projects have explored this topic. Some of these projects are COTTON [2][3][4], PJ08-W1 [5], PJ09-W1 [6], PJ09-W2-44 [7], PJ32-W3 [8], and the currently-going projects of ISLAND, HARMONIC and SMARTS. COTTON was based on Capacity Optimisation in Trajectory-based Operations (TBO). This project considered the use of a pre-defined set of configurations and the election of the optimal one based on TBO. PJ09-W1 and PJ08-W1 are the preliminary projects to PJ09-W2-44. PJ08-W1 focused on Advanced Airspace Management, while PJ09-W1 dealt with an Advanced Demand and Capacity Balance (DCB) concept. The merge of both these projects led to the integration of the DAC concept within the DCB process, the objective of PJ09-W2-44.

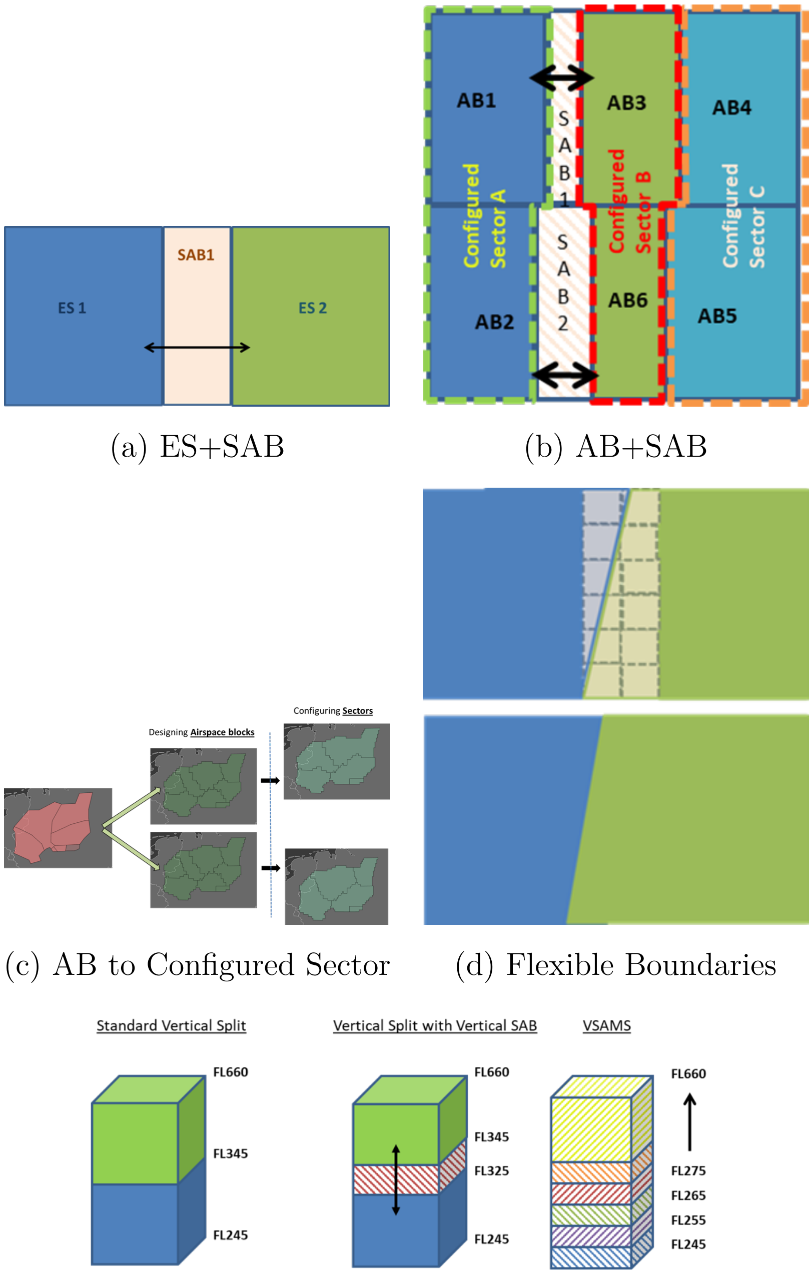
2.1.1 Airspace Building Blocks

Among the SESAR projects dsescribed above, PJ08-W1 introduced 5 different airspace design elements, which can be combined resulting in a Configured Sector. These airspace design elements are defined in the following list:

- Elementary Sector (ES), an ATC workable 3D airspace that cannot be split into a controllable sector.
- Airspace Block (AB), a primary volume that needs to be merged with other AB to conform a workable sector.

- Shareable Airspace Block (SAB), a non-controllable sector that needs to be attached to any adjacent ES or AB to build an operating sector. That is, no operating sector can be comprised of only SABs.
- Flexible Boundaries, sector boundaries that can be modified or refined to facilitate/optimise Free-Route trajectories.
- Vertical Shareable Airspace Block (VSAB), this non-workable sector is the same concept as a SAB, but in the vertical plane. It splits the space vertically and typically cover 1.000 to 4.000 ft.

The combination of these design elements is depicted in Fig. 2.



(a) ES+SAB (b) AB+SAB

(c) AB to Configured Sector (d) Flexible Boundaries

(e) VSAB

Figure 2: DAC Airspace Design Elements Combination

2.1.2 DAC levels of implementation

This section provides an overview of the different levels of implementation of the DAC by the combination of the airspace design elements described in the previous section.

Level 1

The first level of DAC implementation is the foundational stage, utilizing existing tools and processes to manage airspace congestion. It includes automated support for sector design and optimizes routes based on real-time demand and capacity assessments. With this level of implementation licensing and training protocols remain consistent with current standards. Project W1-PJ08, which aimed to implement this level, focused on enhancing the efficiency of airspace management without introducing new methodologies or technologies.

Level 2

The second level of DAC implementation introduces new tools and processes like the spot management tool and the balanced prediction network monitoring tool. Airspace is configured into blocks that are later transformed into new sectorisations to optimize airspace structure for enhanced efficiency during varying traffic patterns. Licensing and training undergo slight modifications in this level of implementation but not significantly. In implementing this level, Project W2-PJ9.44 needed to focus on integrating these new tools effectively while ensuring that the transition does not disrupt current operations.

Level 3

The third level of DAC implementation integrates DAC with Integrated Network Management ATC Planning (INAP), enabling automatic triggering of DAC measures in response to INAP forecasts. Shareable Airspace Blocks (SAB) are introduced at this level but are not workable alone; removal from one sector to another does not affect their viability or safety elements can be removed from them without affecting their integrity. Projects HARMONIC and ISLAND, What aim at the seamless integration of these advanced features ensuring enhanced coordination procedures and adaptive route structures for improved air traffic flow.

Level 4

The fourth level of DAC implementation continues with shareable airspace blocks but introduces significant changes in licensing and training protocols compared to previous levels. This level isn't being implemented nor studied by any project at the moment; however, it implies a more complex integration of technology and human factors requiring extensive retraining of personnel involved in air traffic control.

Level 5

Finally, the fifth level of DAC implementation marks a radical shift by introducing flexible boundaries facilitating free route trajectory regardless of flow patterns making it the most advanced implementation level involving comprehensive use of all DAC tools/processes as well as a complete overhaul in licensing/training protocols making them radically different from previous levels. The SMARTS project aiming at this level involves more exploratory research and development efforts coupled with rigorous testing/validation processes given its complexity and innovative nature.

2.2 Demand Measures Optimisation

The literature on air traffic demand measures optimisation presents a range of approaches to address the challenges of managing air traffic flow. [9] proposes an integer programming model for large-scale air traffic flow management (ATFM) that covers all phases of each flight and allows for rerouting decisions. This model has the potential to identify promising ATFM interventions on a national or continental scale. [10] discusses the transition from the current ATFM to a futuristic model where flights are assigned delays with massive cherry-picking measures. Their results suggest that hybrid models could be a viable option for reducing delays with minor changes in the current ATFM paradigm.

A different approach is presented by [11], who proposes a sector network model to analyse spatiotemporal sector interdependencies and evaluate capacity enhancement possibilities for sectors unable to meet dynamic demand. This short-term ATM mechanism could reduce traffic peaks for the whole European airspace. [12] present an enhanced demand and capacity balance (EDCB) formulation that considers alternative trajectories to capture user-driven preferences. Their results show that the EDCB could reduce the minutes of delay by 70%.

Meanwhile, [13] proposes an ATFM framework that scrutinises the stochastic nature of ATS through a chance-constraint-based probabilistic approach. Their two-stage model enhances scalability and minimises the NP-hard nature of the overall problem. [14] proposes a new mechanism to apply a strategic shifting of ETOT with their CTOT windows to reduce the probability of ATCo interventions. This contributes to the well-accepted and widely spread research topic TBO that enhances the design of new Decision-support tools. [15] discusses the PARTAKE project, which fosters adherence of air space user's trajectory preferences enhancing Trajectory Based Operations (TBO) concepts by identifying tight interdependencies between trajectories.

Finally, [16] introduces a novel approach for synchronised demand-capacity balancing within a proposed Collaborative Air Traffic Flow Management framework. Their approach realises optimising traffic flow and scheduling airspace configuration in a more harmonised manner. [17] presents an approach that takes alternative trajectories into a DCB optimisation algorithm. Their results suggest that delays can be remarkably reduced once alternative trajectory options are included in the DCB algorithm. [18] proposes a method to synchronise traffic flow optimisation and sector opening scheduling, with the aim of achieving flexible demand and capacity balancing (DCB). [19] proposes an optimisation algorithm based on adaptive large neighbourhood search, which is able to determine the best set of regulations minimising air traffic flow management delay from scratch.

3 Formulation of the problem

One of the main objectives of the HARMONIC project is the development of a DCB solver that selects the best combination of demand and capacity balancing measures.

In this context, this thesis is part of the pre-tactical tool used by the Local Traffic Manager (LTM) to select the best DCB measure to solve any imbalance encountered. The problem raised is obtaining the best very short-term ATFCM measures (VSTAM) in order to solve a given short-term imbalance that cannot be resolved by a change in the airspace configuration. This chapter presents the conditions in which the problem of this thesis will be tackled, both by describing the airspace design and the timeframe in which these VSTAM measures will be applied.

3.1 Airspace Design

The HARMONIC project proposes the short-term implementation of the concept of Dynamic Airspace Configuration (DAC). With the use of this concept, there are more opportunities to maximise the capacity of airspace. It enables a more flexible configuration definition that can adjust to changes in air traffic demand. As it would optimise their ATC resources and improve their ability to adjust to different levels of demand -a trait that is typical in many airspaces- this strategy is highly appealing to ANSPs.

Following the definition of the different DAC Airspace design elements and their levels of implementation presented in the previous chapter, the HARMONIC project will be focused on Level 3 of implementation just using VSAB elements in the Madrid ACC sectors (see Fig. 3).

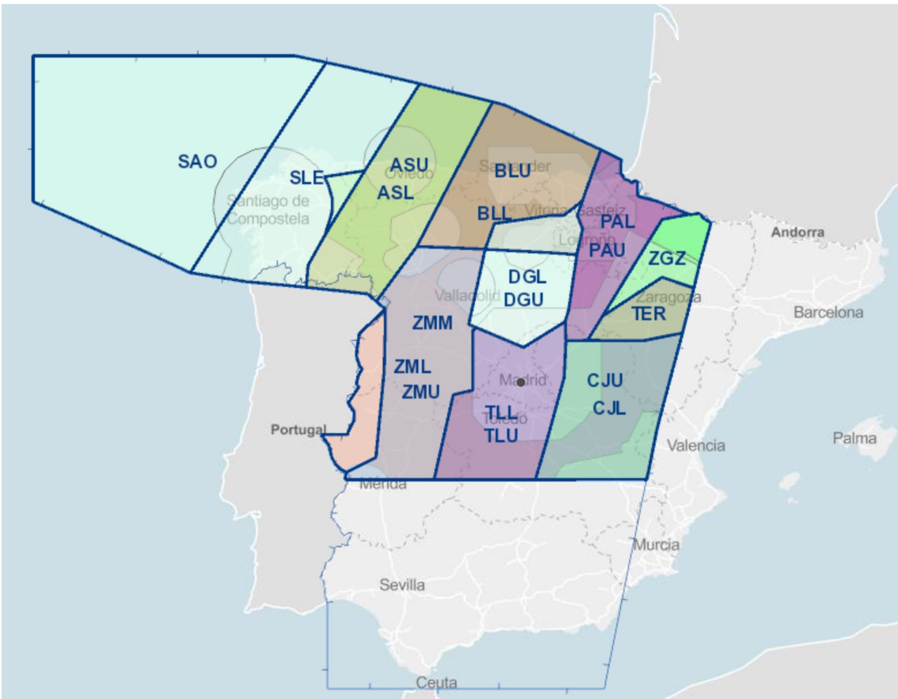


Figure 3: Madrid ACC horizontal sectors.

Similarly to the sectorisation proposed in SESAR PJ.09-W2-S44, three vertical cuts were added to all sectors of Madrid ACC, obtaining three Vertical Shareable Airspace Blocks (VSAB). These cuts would substitute the single fixed cut at FL345 present in current sectorisation. This new approach allows for a more equitable share of traffic between upper and lower sectors. Usually, the upper sectors of the Madrid ACC are more loaded than the lower sectors in terms of air traffic demand. These new cuts allow the readjusting of some of this traffic from the upper to the lower sector, balancing the loads between them.

For the decision of which flight level division would be the most desirable, an analysis of the RFL distribution of the flights crossing Madrid ACC was carried out. As shown in Fig. 4, the percentage of flights that cross the current lower sectors is around 20% of the total number of flights, while for the upper sectors is around 80%.

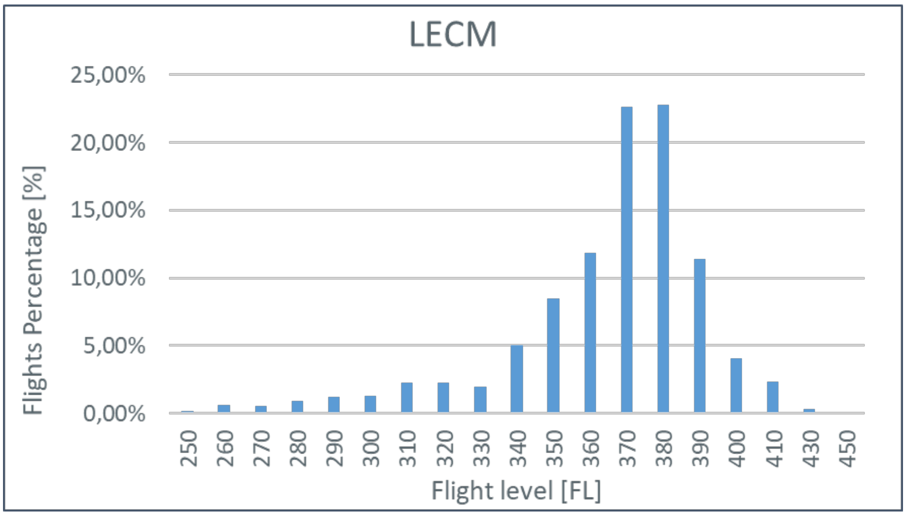


Figure 4: Percentage of total number of flights per RFL.

Using this analysis, the percentage of the total number of flights for each flight level is considered and three different VSAB are proposed. The final vertical cuts are defined at FL325, FL345, FL365 and FL375, creating three 2000-feet VSAB, as defined in Fig. 5.

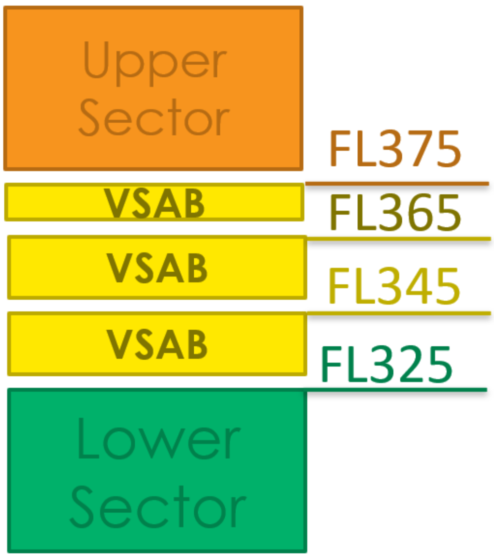


Figure 5: HARMONIC DAC sectors' vertical design.

The logical and spatially ordered associations of these VSABs with the upper and lower elementary sectors lead to the creation of a set of configured sectors for all Madrid ACC. The following section proposes the implementation of this DAC scenario along the different timeframes.

3.2 DCB/DAC Measures Implementation Timeframe

The capability to dynamically manage airspace is extended to the very late planning phase leading into execution. This introduces those actors responsible for ATC in addition to those responsible for ATFCM. This will be the Integrated Network and ATC Planning (INAP) phase, in which local DCB actors and Extended ATC Planning actors work in an environment in which access is provided to all capacity and flow/trajectory management options, with shared ATFCM/ATC situation awareness on both the DCB and ATC sides. These actors should be supported by an automated system and interface to allow them to detect, manage and monitor complex local situations in a fully collaborative way. The system provides an assessment of evolving traffic situations and supports INAP actors in the evaluation of opportunities to smooth flows and de-conflict flights across the INAP area of responsibility, permitting the identification and management of the best-performing option between Dynamic Airspace Configuration measures and STAM in order to resolve hotspots.

Integrated DAC/DCB solutions, while traditionally applied in the planning phase, are moving towards the execution phase. The ultimate objective is seamless integration from the planning phase to execution facilitated by tools that will provide ATFCM/ATC situation awareness on both the DCB and ATC sides and which will be shared between DCB and extended ATC planning actors.

In this context, as we enter into the execution phase and the flight predictions are more accurate, there could be small unforecasted hotspots, which could not be solved by reconfiguring the airspace with the available resources, nor by establishing ground delays —as some of the flights involved may already be airborne. That is the case in which level-capping and re-routing VSTAM measures would be applied. The following chapter details the proposed mathematical model to optimally carry out a cherry-picking procedure for level-capping and re-routing measures at T0-1h (one hour before operation).

4 Methodology

After the literature review presented in Chapter 2, and in the context of the problem proposed in Chapter 3, this chapter presents the mathematical model developed to determine the best set of VSTAM measures to solve a given short-term imbalance, further expanding the capabilities of the integrated DAC / DCB solutions proposed by SESAR. After that, an initial algorithm flowchart is described. Finally, a set of regulation scenarios is identified to validate the model.

In the HARMONIC project, one of the operational elements proposed to further broaden the integrated DAC/DCB solutions is the concept of a DCB solver, which would solve complex and cross-border DCB problems by combining optimised regulations and an optimised cherry-picking solver. In that context, a DCB-cherry picking solver based on heuristics has been developed from a local perspective by building a cost function that determines which flights should be affected by the solution and by which measure. The main objective of this thesis is to develop such a cost function and to demonstrate its benefits.

4.1 Mathematical model

This section describes the calculation process followed to obtain the cost of applying a VSTAM measure between level-capping and re-routing for each flight at a sector that is overloaded in a given period. First, the inputs needed are described, after that the process of obtaining the complexity is outlined (as well as a brief description of the complexity model developed by CRIDA), and finally, the cost function is defined.

4.1.1 Input Data

The first step in the cherry-picking solver calculation process is to determine the data needed as input. The different input elements for this cost function are described is the following sections.

- Optimising period: This corresponds to the period in which the occupancy counts are exceeded for a given configured sector.
- Overloaded sector: This corresponds to the configured sector whose occupancy counts are exceeded and in which some VSTAM measures might need to be applied.
- Neighbouring sectors: This corresponds to the configured sectors bordering the overloaded sector —both horizontally and vertically—, which could absorb some of its traffic through one VSTAM.
- Occupancy peak thresholds: This is the absolute maximum number of flights that can be managed at any given time in a sector. These thresholds are typically defined for 5-minute periods.
- Flight plans in INAP time frame: This corresponds to the flight plan information available at the time of VSTAM application —typically 60/20 minutes before operation. The detailed flight plan information that is needed as input is defined in the following section as the data needed for complexity computation.

4.1.2 Sector Complexity

One of the key elements in this cost function calculation is the complexity of a sector. For this computation, the algorithm eCOMMET [20][21] —developed in CRIDA— has been used because it provides the complexity per flight and is represented through an equivalent occupancy count. This section provides an overview of the key elements used by the algorithm eCOMMET to compute the complexity.

At the beginning of the complexity computation, all flights crossing the sector are considered to have the same base complexity of value slightly less than 1. From that point, the following factors are considered for each of the flights:

Standard flow belonging

For each flight present in the sector, it is assessed whether or not the flight can be assigned to any of the flows existing in the sector, taking into account the following criteria:

- Similarity of the ICAO route (broken down by airways and SID/STAR procedures according to the ADEP/ADES runway activation plan) with the route defining the flow.
- Coincidence of flight attitude and flow attitude (climb / descend / cruise).
- Time spent in the sector (to avoid short crossings).

Belonging to a standard flow reduces the complexity of the traffic, as ATCo will be familiar with the procedures of that flight. If any of the conditions are not met, the flight is considered outside the standard flows and it is assigned a factor that is added to the base complexity.

Interaction severity

This relates to the severity of the interaction between flows within the sector. This term is very relevant for the calculation of complexity, as the nature of the flows has a significant influence on the complexity of the traffic. The interaction severity factor is calculated once the geometry of the flows of a sector is defined, regardless of the traffic.

The following list gathers possible interactions between flows ordered by their severity.

- Interaction in the same flow
- Interaction Cruise-Cruise
- Interaction Cruise-Evolution
- Interaction Evolution-Evolution

Flights in evolution

For each flight present in the sector, the attitude at the entry, midpoint, and exit of the reference airspace associated with the sector is evaluated.

- If all three attitudes correspond to cruise, the flight will be considered an established flight.
- If any of the attitudes correspond to the climb or descend phase, the flight will be considered an evolving flight and it will be assigned a complexity factor depending on the amount of vertical space covered by the flight.

In the particular case where the flight has an attitude of climb at the entrance of the sector, an attitude of cruise inside, and an attitude of descent at the exit, the complexity is greater because it has so many changes in attitude, so it will also be assigned a complexity factor.

Military flights

For each flight present in the sector, it is assessed whether the flight is affected by military activity:

- IFR military flight, identified by aircraft type. This type of aircraft is considered to slightly increase complexity values.
- Civil IFR flight assigned to standard flow with military delta affection. This affection is considered to affect considerably the complexity.

Transoceanic flights

For each flight present in the sector, it is assessed if its origin / destination is located in the other side of the Atlantic Ocean, and its origin / destination is one of the Spanish airports. If both conditions are met, the flight will be considered transoceanic and assigned a complexity factor.

Once these conditions are assessed for each flight, the sector complexity is computed for each 5-minute period every minute within the interval of study. These values then can be considered as equivalent occupancy count for overload/underload evaluation.

The application of this complexity in the cost function for VSTAM implementation is related to the impact of removing each flight from the overloaded sector, as well as the impact of adding it to one of the neighbouring sectors. That is why the following complexity computations are carried out in order to build the cost function:

- Original complexity values: these values correspond to the 5-minute period complexity values of the overloaded sector and its neighbouring sectors, according to the flight plans available at the given time frame.
- Complexity values without a given flight: for each flight crossing the overloaded sector in the optimising period, the complexity values of the sector are computed considering this flight is removed from the computation. The difference in complexity when removing a given flight can be seen in Fig. 6.
- Complexity values of the neighbouring sectors with a given flight: for each flight crossing the overloaded sector in the optimising period, the complexity values of the neighbouring sectors are computed assuming this flight is added to this other sector. For that, we need to distinguish two different cases, depending on the VSTAM:
  - Level-capping: in this case, we need to consider that the flight would be performing a late climb or an early descent. For that, the entry and exit times and flight levels will be modified accordingly, as if the flight would never cross the overloaded sector.
  - Re-routing: in this case, we will consider that the flight enters the lateral sector at the same time it was supposed to enter the overloaded sector, and exits after the time required to cross the lateral sector has passed considering constant cruise speed.

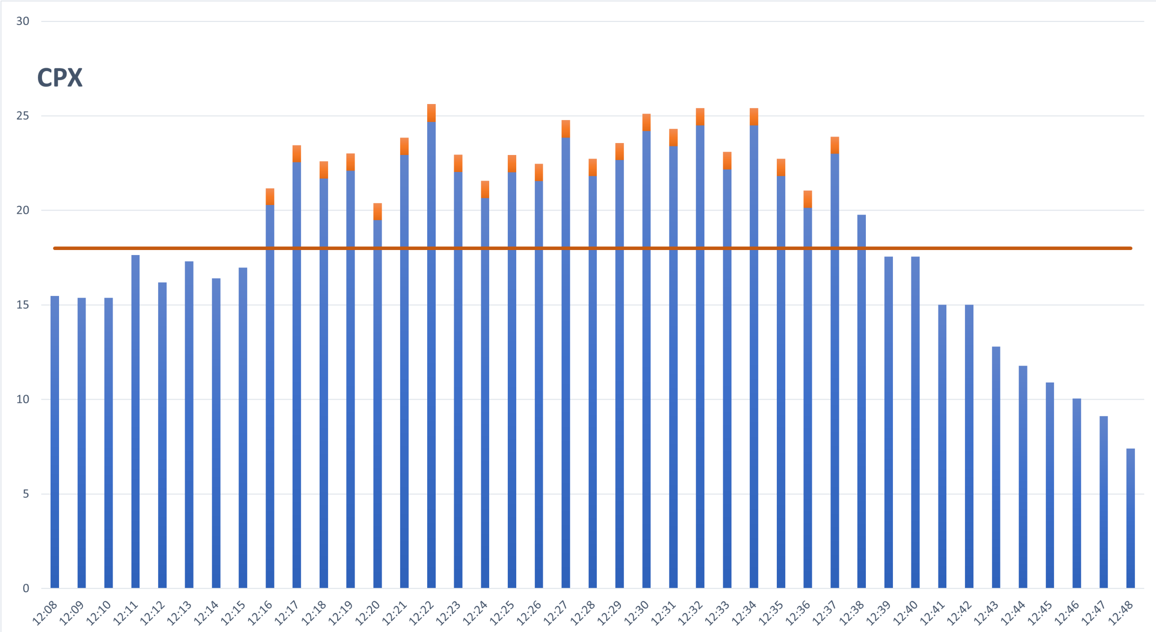


Figure 6: Impact of removing a flight from a given overloaded sector in its complexity values.

4.1.3 Cost Function

The cost function for the VSTAM selection optimisation problem is defined as the sum of costs for applying a certain measure to a certain flight. This sum —represented in Eq. 1— will consider all flights inside the overloaded sector during the optimising period and the possible VSTAMs considered in this thesis: Level-Capping and Re-routing to a lateral sector.

$$F(x) = \sum_{i}^{F}\sum_{j}^{M} x_{i,j}C_{i,j} \qquad i \in F; j \in M; x_{i,j} \in 0,1 \tag{1}$$

where:

- $x_{\mathrm{i,j}}$ is the decision variable to apply the measure j to flight i.
- $C_{\mathrm{i,j}}$ is the cost of applying the measure j to flight i.
- F is the set of all flights.
- M is the set of all measures considered.

The cost of applying a measure is defined as the product of two elements. The first element is related to the impact on the complexity values of removing the aircraft from the overloaded sector to another sector (either by Level-Capping or Re-routing). The second element represents the impact on the aircraft for the application of the measure. Eq. 2 represents this cost of applying a measure.

$$C_{i,j} = \frac{1 + CPX_{overloadedsector}}{1 + CPX_{othersector}} c_{i,j} \qquad i \in F; j \in M \tag{2}$$

where:

- $CPX_{\mathrm{overloaded\ sector}}$ is the sum of the differences of complexity values when the aircraft i has been removed from the sector. These differences are only added to this sum when the initial complexity values exceed the peak threshold value.

- $CPX_{\text{other sector}}$ is the sum of the differences of complexity values when the aircraft i has been added to the sector. These differences are only added to this sum when the initial complexity values exceed the peak threshold value.
- $c_{i,j}$ is the cost on the flight i when applying measure j.
- F is the set of all flights.
- M is the set of all measures considered.

The cost of applying a certain measure on a given aircraft has a different definition depending on the type of measure.

Level Capping

When applying a level capping measure, the cost of the flight is related to two factors. The first factor is the vertical distance between its Reference Flight Level (RFL) and the vertical split level between the upper and lower sectors. The second factor is the distance from the overloaded sector's centroid to the airport of origin or destination. These factors are then nondimensionalised using the maximum value. Eq. 3 represents how this cost for a level capping measure is applied.

$$c_{i,0} = (1+\frac{VerticalLimit - RFL_i}{\max_{i\in F}(VerticalLimit - RFL_i)})(1+\frac{\min(dist_{ADEP_i}, dist_{ADES_i})}{\max_{i\in F}(\min(dist_{ADEP_i}, dist_{ADES_i}))}) \qquad i \in F \tag{3}$$

where:

- RFL_i is the reference flight level for flight i.
- $dist_{ADEP_i}$ is the distance from the overloaded sector's centroid to the airport of origin of flight i.
- $dist_{ADES_i}$ is the distance from the overloaded sector's centroid to the airport of destination of flight i.
- *VerticalLimit* is the flight level of the limit between the upper and lower sectors.
- F is the set of all flights.
- j is considered of value 0, as the level capping is only one of the set of measures.

Rerouting

When applying a rerouting measure, the main cost of the flight is related to the additional distance flown with respect to the planned one. This factor is also nondimensionalised using the maximum value from the whole set of rerouting options and flights. Eq. 4 represents how this cost for a rerouting measure is applied.

$$c_{i,j} = 1 + \frac{addDist_{i,j}}{\max_{i\in F, j\in S}(addDist_{i,j})} \qquad i \in F, j \in S \tag{4}$$

where:

- $addDist_{i,j}$ is the additional distance flown by flight i because of the rerouting measure j.
- F is the set of all flights.
- S is the set of all possible rerouting measures. Note that this is a subset of the set M, which includes all the possible VSTAM measures considered (including level capping measures).

4.2 Algorithm flowchart

This section describes the process followed in this thesis to obtain the VSTAM measures with the minimum cost values for a given overloaded sector. This process is then used to validate the mathematical model defined in the previous section. This process is represented in Fig. 7.

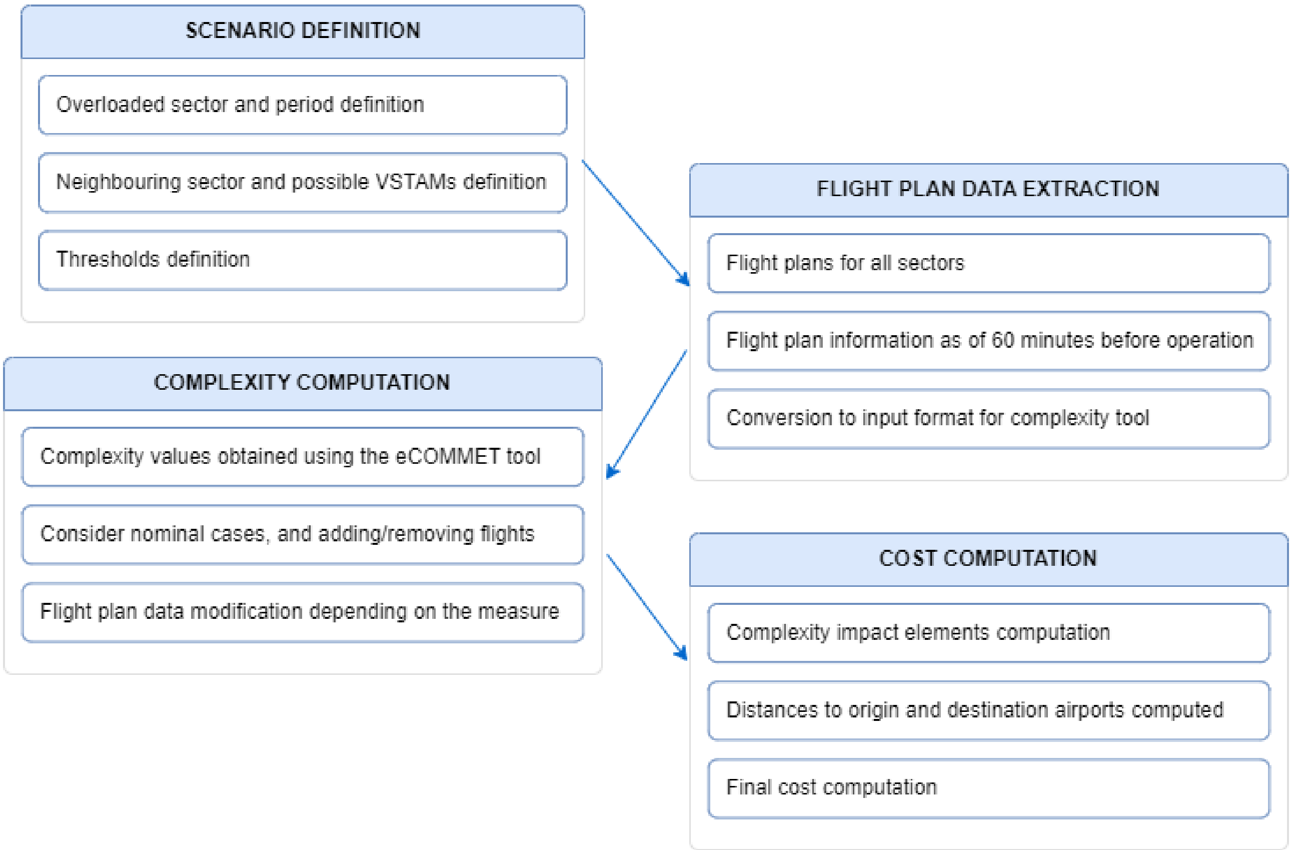


Figure 7: Flowchart for the process of obtainint the cost values.

4.2.1 Scenario definition

The first step of the process is to define the whole VSTAM optimisation scenario. First, a sector with a particularly overloaded period expected is identified. The overload period is defined as any 5-minute period in which the complexity values of a sector exceed the peak occupancy thresholds defined in [22], as these values are defined to be the absolute maximum number of flights an ATCo is capable of managing at the same time in that sector.

Once this overloaded sector of study is determined, an assessment of its neighbouring sectors' complexity is carried out in order to check whether they are able to absorb some of the traffic from the overloaded sector. The ones that do are then considered for VSTAM measure selection. Two cases are then identified:

- If the neighbouring sector is located below or above the overloaded sector, then a level-capping measure is made available. The vertical limit between the sectors is also identified.
- If the neighbouring sector is located lateral to the overloaded sector, then a rerouting measure is made available to that sector.

Note that only one level capping measure is possible, but many rerouting measures can be made available.

4.2.2 Flight plan data extraction

The following phase includes the flight data extraction. In particular, the needed information is all flights planned to be in a particular sector during the interval of study 60 minutes before operation. The following list contains all the fields needed for the complexity computation:

- Callsign: identification of the flight.
- Origin Airport: ICAO code for the departure airport.
- Destination Airport: ICAO code for the arrival airport.
- RFL: reference flight level, which corresponds to the expected cruise flight level.
- Cruise Speed: expected speed during the cruise phase, in knots.
- Flight Rules: instrumental flight rules or visual flight rules.
- Aircraft Type: ICAO aircraft type designator
- ETOT: expected take-off time.
- Expected Entry Time: expected time of entry to the sector.
- Expected Exit Time: expected time of exit to the sector.
- Expected Entry Flight Level: expected flight level of entry to the sector.
- Expected Exit Flight Level: expected flight level of exit to the sector.
- Entry Attitude: expected attitude at the entry of the sector, which can either be climb, cruise or descend.
- Exit Attitude: expected attitude at the exit of the sector, which can either be climb, cruise or descend.
- Waypoint Route: succession of waypoints and navigation aids that the flight is expected to follow inside the Spanish airspace. This route is then used to assign the flight to one of the standard flows identified in each sector.

For this thesis's validation, this information has been mainly extracted from the CRIDA database's model GIPV, which stores all flight plan updates received by the flight data processing system (FDPS) in ENAIRE.

This information is obtained for the overloaded sector and the neighbouring sectors considered for the VSTAM measures, and then it is converted to the input format needed for the complexity computation. An example of this format can be found in the Annex 5.2.

4.2.3 Complexity computation

The next step is the computation of the complexity values for the overloaded sector and the neighbouring sectors using the algorithm eCOMMET developed in CRIDA. Not only these complexity values are obtained using the flight information obtained in the previous section, but also the values in case each flight is removed from the overloaded sector and added to one of the neighbouring sectors. This is done to evaluate the impact on the different airspaces of moving one flight from one sector to another.

In order to obtain this impact, every flight in the overloaded sector is removed from the input file for the complexity computation for that sector and added to the neighbouring sectors'. To do that, the times of entry and exit need to be modified according to the type of measure expected.

Level capping

When adding a flight to the upper/lower sector for a level capping measure, the entry and exit attitudes —as well as their entry and exit flight levels— are to be modified considering the flight would be performing a late climb or an early descent. Another case would be if the level capping were to be applied to a flight in the cruise phase during the whole crossing of the sector; in that case, only the entry and exit levels would be modified.

Flights in the case of a late climb when a level capping is implemented can be detected if they are also present in the lower sector and exiting it in an attitude of climb. These flights are considered to be established at the flight level just below the vertical limit and exiting the sector with a cruise attitude, just as it is represented in Fig. 8. The exit time for those flights will be considered the same as the exit time in the overloaded sector.

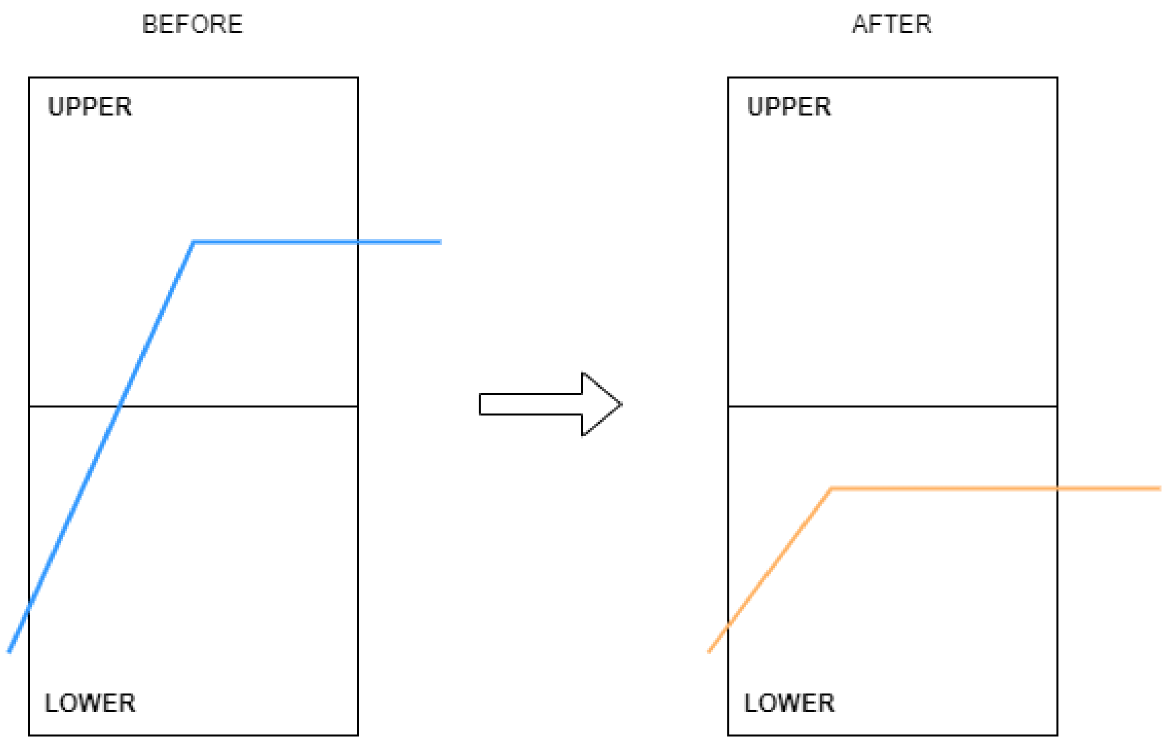


Figure 8: Modification of the trajectory in case of a late climb

In the case of flights with an early descent when a level capping is implemented, they can be detected if they are also present in the lower sector and entering it in an attitude of descent. These flights are considered to descend to the lower sector just before entering it and are established at the flight level just below the vertical limit, just as it is represented in Fig. 9. The attitude of entry is then considered to be cruise and their time of entry is considered to be the same as the one in the overloaded sector.

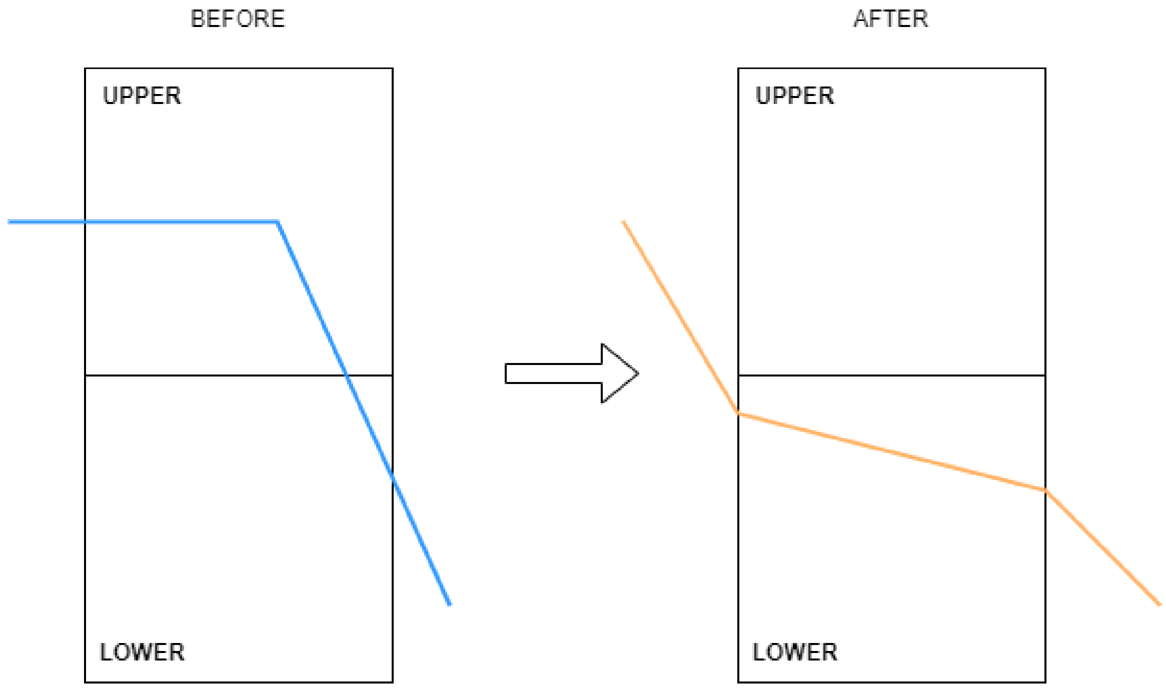


Figure 9: Modification of the trajectory in case of a early descent

Finally, those flights which are not detected to be also present in the other sector, are considered to be in a cruise phase along the sector. These flights are only modified so that they enter the lower or upper sector just below or above the vertical limit.

Rerouting

When adding a flight to a lateral sector for a rerouting measure, an alternative route must be considered. The entry time to the lateral sector is considered to be the same as the one in the overloaded sector. However, since this alternative route will add miles to the total distance covered, the exit times must be calculated considering a constant cruise speed.

Once these input complexity files are modified, the complexity values for the optimising period are computed for all the sectors and the cases —nominal, adding, and removing flights. These complexity values are then ready to be used in the cost computation.

4.2.4 Cost computation

The final step in the process is to define all the elements that make up the cost equation defined in previous sections. These elements can be computed or found with the information extracted in previous steps.

The complexity elements in the cost function are computed as the difference in the complexity values considering the specific flight at the times in which these values exceeded the declared thresholds for the sector.

For the level-capping options, the distances with the airports of origin and destination need to be computed. For that, the coordinates of all the airports are obtained and the distance with the sector polygon is computed in a database query. Finally, the additional distance flown is computed for all the different rerouting options provided.

All these values are then stored in a matrix which is then used to compute the final cost values according to the equations defined in the previous section. An example of this cost matrix can be found in Fig. 10.

callsign		Cost	CPXdiff	CPXother	diffLevel	minDistAdepAdes	rerouteDist
TAP782	LC	0.0379008	44.19	0	15	494489	NaN
	RR	0.0442576	44.19	0	NaN	NaN	117.7
RYR3NE	RR	0.0447527	43.69	0	NaN	NaN	117.7
EZY95HN	RR	0.0457561	42.71	0	NaN	NaN	117.7
EWG603	LC	0.0461033	36.15	0	15	494489	NaN
TAP1336	LC	0.0461033	36.15	0	15	494489	NaN
EZY95HN	LC	0.0464473	42.71	0	15	787228	NaN
EXS7JN	RR	0.0491884	39.66	0	NaN	NaN	117.7
EJU49FH	LC	0.0499482	36.15	0	15	626197	NaN
EXS43YJ	RR	0.0500877	38.93	0	NaN	NaN	117.7
RYR3NE	LC	0.0507878	43.69	0	15	1.00807e+06	NaN
EXS72U	RR	0.0511902	38.07	0	NaN	NaN	117.7
EXS92YB	RR	0.0511902	38.07	0	NaN	NaN	117.7
EZY13TQ	RR	0.0529521	36.77	0	NaN	NaN	117.7
EXS7JN	LC	0.0533864	39.66	0	15	916764	NaN

Figure 10: The cost elements and final cost are stored in a matrix.

4.3 Validation scenario

The development of this thesis is part of the initial concept analysis for the SESAR project HARMONIC, in which the airspace of study is Madrid ACC. The objective of selecting a particular scenario to define the optimal VSTAM selection is to assess the benefits that the application of the cost function defined in the previous section to tackle a specific local short-term imbalance would have in the management of this complex airspace.

The validation of this cost function will then be carried out by selecting a particular elementary sector —as it cannot be further split to accommodate more traffic— from ACC Madrid and a particular date in which said sector had to be regulated, causing delay into the European network. Fig. 11 represents the amount of daily delay caused by ATC capacity in the Madrid ACC for the summer period of 2022. One of the days with the most amount of delay is September 13th, 2022.

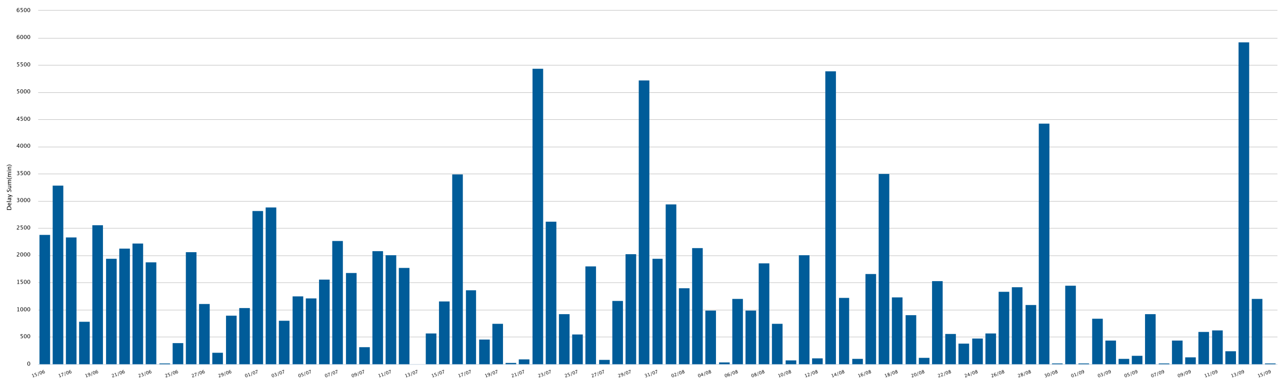


Figure 11: Daily Delay in Madrid ACC for the summer period of 2022.

From that day, the amount of actual delay in minutes for each regulated sector in the Madrid ACC has been extracted and represented in Table 2. The sector with the most delay is the one with code LECMBLU, which is the upper sector of the Bilbao area, represented along with the planned trajectories for that period in Fig. 12.

Sector Code	Sum of delay (minutes)
LECMBLU	909
LECMDGU	481

Table 2: Amount of delay in Madrid ACC per sector for the date 13/09/2022

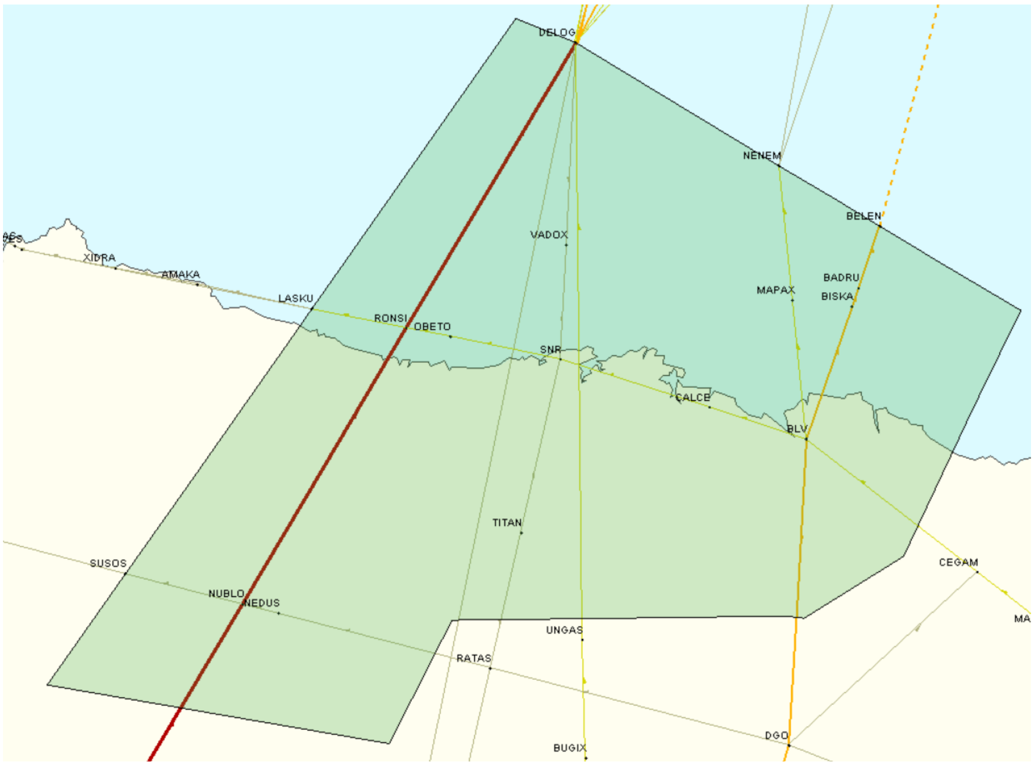


Figure 12: Bilbao upper sector and the trajectories planned for the regulated period.

One of the most delayed intervals for that day in LECMBLU is the period between 12:00 and 13:00. The flight plan information available 60 minutes before operation for the flights expected to be in the sector within this interval is obtained and represented in Fig. 13. The query used to extract this information is included in Annex 2.

flightKey	latestFP	lastAdep	lastAdes	RFL	Speed	flightRules	aircraft	expectedEntryFL	expectedExitFL	ExpectedEntryTime	ExpectedExitTime	AttitudeIn	AttitudeOut
17348801	10:29	LEBL	KJFK	360	489	IFR	B772	360	360	12:03	12:16	CRUISE	CRUISE
17349410	10:14	LEBL	KPHL	380	495	IFR	B788	380	380	12:38	12:51	CRUISE	CRUISE
17348340	04:39	LEMG	LFPG	340	426	IFR	A319	360	360	12:20	12:33	CRUISE	CRUISE
17348357	10:54	LPPT	LFPG	340	440	IFR	BCS3	360	360	11:55	12:12	CRUISE	CRUISE
17348066	03:53	LPFR	EBBR	360	437	IFR	A320	360	360	11:57	12:14	CRUISE	CRUISE
17348140	07:45	LPPT	EDDF	340	443	IFR	A321	360	360	11:55	12:12	CRUISE	CRUISE
17348579	05:23	LPFR	EGCC	400	438	IFR	C68A	400	400	12:34	12:51	CRUISE	CRUISE
17347780	10:54	LEMG	EIDW	380	456	IFR	A333	380	380	12:45	12:57	CRUISE	CRUISE
17348275	10:55	EIDW	LEMG	350	449	IFR	A320	350	350	12:49	13:02	CRUISE	CRUISE
17348573	05:23	LPFR	EDDB	360	440	IFR	A320	360	360	12:25	12:42	CRUISE	CRUISE
17348336	04:37	LPPT	EDDK	360	453	IFR	B738	360	360	12:25	12:42	CRUISE	CRUISE
17348303	04:30	GCTS	EGSS	360	447	IFR	B738	360	360	12:09	12:26	CRUISE	CRUISE
17348403	04:52	GCRR	EGNX	360	437	IFR	B738	360	360	12:38	12:55	CRUISE	CRUISE
17348264	10:56	GCRR	EGNM	360	438	IFR	B738	360	360	12:53	13:10	CRUISE	CRUISE
17348234	04:17	GCRR	EGSS	360	439	IFR	B738	360	360	12:03	12:20	CRUISE	CRUISE
17347572	10:06	LEMG	EGBB	340	447	IFR	A321	360	360	12:13	12:22	CRUISE	CRUISE
17347598	10:06	LEMG	EGNX	360	435	IFR	B738	360	360	12:19	12:28	CRUISE	CRUISE
17348305	04:31	GCFV	EGSS	360	441	IFR	B738	360	360	12:16	12:33	CRUISE	CRUISE
17347517	10:55	LEMG	EGNT	360	439	IFR	B738	360	360	11:53	12:06	CRUISE	CRUISE
17348263	04:22	GCFV	EGNM	360	440	IFR	B738	360	360	12:06	12:23	CRUISE	CRUISE
17348567	05:22	GCTS	EGBB	360	446	IFR	B738	360	360	12:24	12:41	CRUISE	CRUISE
17348289	10:02	GCRR	EGBB	360	439	IFR	B738	360	360	12:23	12:40	CRUISE	CRUISE
17348383	04:46	GCTS	EGNM	360	444	IFR	B738	360	360	12:24	12:41	CRUISE	CRUISE
17348326	04:35	LSGG	LEST	390	438	IFR	A20N	390	344	12:37	12:41	CRUISE	DESCEND
17348167	08:59	GCRR	EGKK	360	449	IFR	A21N	360	360	12:15	12:32	CRUISE	CRUISE
17348409	04:54	EGKK	LEMG	390	439	IFR	A319	390	390	12:36	12:49	CRUISE	CRUISE
17348268	10:37	GCTS	EGGD	380	447	IFR	A20N	380	380	12:28	12:45	CRUISE	CRUISE
17348394	04:50	EGKK	LEMD	390	442	IFR	A319	390	343	12:28	12:34	CRUISE	DESCEND
17348367	10:52	EGKK	LEZL	390	438	IFR	A319	390	390	12:42	12:55	CRUISE	CRUISE
17348136	10:11	GCFV	EGKK	360	441	IFR	A320	360	360	11:53	12:10	CRUISE	CRUISE
17348490	05:10	GCRR	EGKK	380	444	IFR	A20N	380	380	12:52	13:09	CRUISE	CRUISE
17347858	08:07	GMAD	EGKK	380	438	IFR	A319	380	380	12:23	12:32	CRUISE	CRUISE
17348149	04:02	LPFR	EGKK	360	439	IFR	A320	360	360	11:50	12:07	CRUISE	CRUISE
17348365	04:43	GCTS	EGGW	380	449	IFR	A20N	380	380	12:18	12:35	CRUISE	CRUISE
17347710	10:50	GMMX	EGKK	360	437	IFR	A319	360	360	12:01	12:13	CRUISE	CRUISE
17347660	10:11	LEMG	EGCC	360	436	IFR	A320	360	360	12:17	12:26	CRUISE	CRUISE
17348166	08:59	GCRR	EGGD	360	451	IFR	A21N	360	360	12:21	12:38	CRUISE	CRUISE
17347845	10:54	LEMG	EGAA	360	436	IFR	A320	360	360	12:54	13:07	CRUISE	CRUISE
17348412	08:10	LPMA	EGKK	360	441	IFR	A320	360	360	11:53	12:10	CRUISE	CRUISE
17347521	10:06	LEMG	ENGM	380	445	IFR	B738	380	380	11:59	12:08	CRUISE	CRUISE
17348156	05:11	EGLL	LEMD	350	452	IFR	A20N	350	341	11:57	12:03	CRUISE	DESCEND
17349413	07:35	LEMD	EGLL	340	432	IFR	A20N	360	360	12:16	12:27	CRUISE	CRUISE
17348048	10:47	LPPT	EHAM	380	455	IFR	B738	380	380	12:05	12:21	CRUISE	CRUISE
17348191	04:08	LPPT	ELLX	360	453	IFR	E190	360	360	12:00	12:17	CRUISE	CRUISE
17348148	10:06	LEJR	EGLC	430	410	IFR	E55P	430	430	12:13	12:22	CRUISE	CRUISE
17348236	08:19	ENBR	LEMG	370	448	IFR	B738	370	370	12:16	12:29	CRUISE	CRUISE
17349322	07:21	GMMN	EGKK	380	450	IFR	B738	380	380	12:46	12:58	CRUISE	CRUISE
17347744	02:55	GMTT	EGSS	360	343	IFR	B738	360	360	11:54	12:06	CRUISE	CRUISE
17347800	03:03	GMMX	EGSS	360	445	IFR	B738	360	360	12:07	12:16	CRUISE	CRUISE
17348239	04:18	GCTS	EGGD	360	449	IFR	B738	360	360	11:50	12:07	CRUISE	CRUISE
17347729	10:36	LIPE	LEST	390	441	IFR	B738	370	344	12:06	12:10	DESCEND	DESCEND
17348311	10:36	GCLP	EDDK	360	447	IFR	B738	360	360	12:28	12:45	CRUISE	CRUISE
17348562	10:08	GCLP	EGCC	360	448	IFR	B738	360	360	12:19	12:36	CRUISE	CRUISE
17347516	10:23	LEMG	EGNX	360	439	IFR	B738	360	360	12:06	12:15	CRUISE	CRUISE
17348282	10:23	GCTS	EGSS	360	455	IFR	B38M	360	360	12:31	12:48	CRUISE	CRUISE
17348387	04:47	GCRR	EGNX	360	443	IFR	B738	380	380	12:32	12:49	CRUISE	CRUISE
17348028	10:52	GCRR	EGCC	360	454	IFR	B38M	360	360	11:53	12:10	CRUISE	CRUISE
17347582	10:07	LEAL	EIDW	360	370	IFR	B738	360	360	12:04	12:20	CRUISE	CRUISE
17347644	10:06	LEMG	EGSS	360	437	IFR	B738	360	360	12:16	12:25	CRUISE	CRUISE
17347426	10:49	LEMG	EGBB	400	443	IFR	BE40	400	400	12:31	12:40	CRUISE	CRUISE
17348421	04:56	LPPT	EPWA	340	451	IFR	A21N	360	360	12:45	13:02	CRUISE	CRUISE
17348331	04:36	LPPT	EGKK	360	447	IFR	A21N	360	360	12:25	12:42	CRUISE	CRUISE
17349626	10:36	LPPT	EDDB	360	413	IFR	E190	360	360	12:02	12:20	CRUISE	CRUISE
17348358	04:41	LPPT	EDDL	380	442	IFR	A319	380	380	12:30	12:47	CRUISE	CRUISE
17348467	09:04	LPPT	EDDH	360	452	IFR	E195	360	360	12:55	13:12	CRUISE	CRUISE
17348088	07:38	LPPT	EKCH	320	413	IFR	A20N	380	380	11:45	12:03	CRUISE	CRUISE
17348306	04:31	LPPT	ENGM	380	447	IFR	A320	380	380	12:20	12:37	CRUISE	CRUISE
17348307	10:37	LPPT	ESSA	360	441	IFR	A319	360	360	12:20	12:37	CRUISE	CRUISE
17347728	10:44	GCRR	EHAM	380	446	IFR	B738	380	380	11:46	12:03	CRUISE	CRUISE
17348213	08:25	LFRS	LEMG	330	458	IFR	A319	390	390	12:17	12:28	CRUISE	CRUISE
17347812	10:11	LEMH	LEAS	390	432	IFR	A319	390	342	12:21	12:30	CRUISE	DESCEND
17347189	10:45	LEMG	EGGW	360	452	IFR	A321	360	360	12:36	12:45	CRUISE	CRUISE
17348105	10:56	LPFR	EGKK	360	445	IFR	A21N	360	360	11:44	12:01	CRUISE	CRUISE

Figure 13: Flight plan information of flights inside the LECMBLU sector between 12:00 and 13:00.

The planned complexity values according to the flight plan information 60 minutes before operation are represented in Fig. 14. Comparing these complexity values with the peak occupancy threshold defined for the sector —which is 20, according to [22]—, there was two overload periods expected between 12:00 and 12:07 and between 12:16 and 12:37.

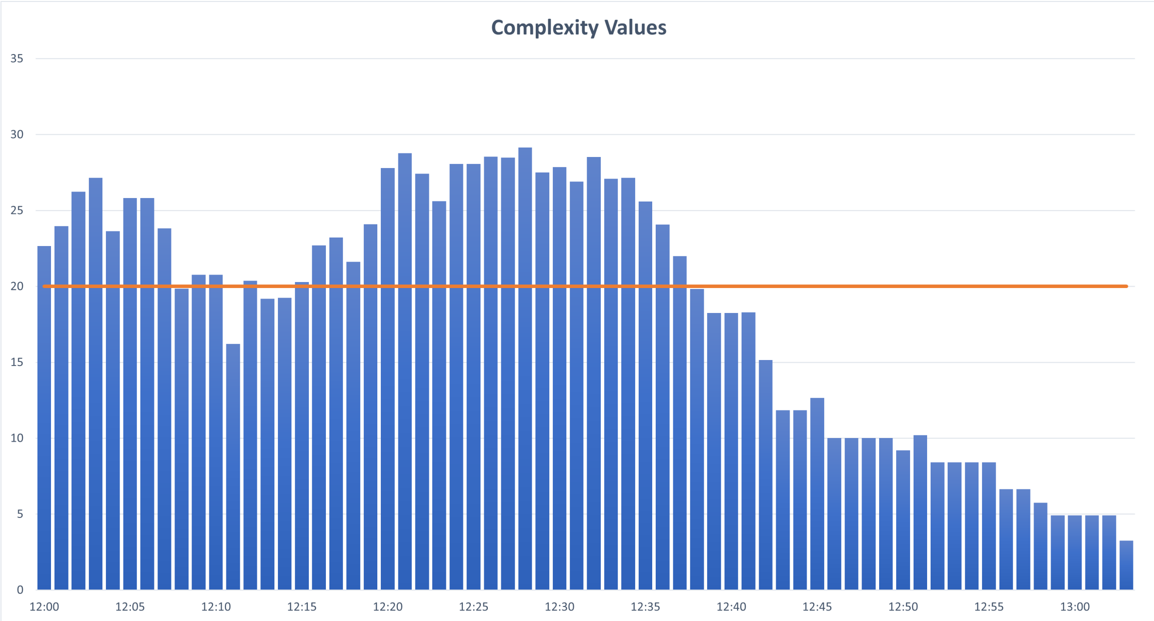


Figure 14: Complexity values of LECMBLU between 12:00 and 13:00

This validation aims to find out what STAM measures to apply according to their cost values from the flight list expected 60 minutes before the operation. The measures considered are the following:

- Level capping to the lower sector, considering that the vertical limit between the sectors is located at FL345.
- Rerouting to the sector LECMASU, located to the west of the sector. This measure is only considered for flights that belong to the western north-to-south flow identified from Fig. 12.

5 Results

This chapter includes a representation and analysis of the results obtained from the application of the cost function to the scenario described in the previous chapter. The VSTAM measures selected to off-load the overloaded sector LECMBLU are listed and the resulting benefits are exposed.

The process described in the previous chapter is followed for the regulated scenario in the sector LECMBLU at the date 2022-09-13. The cost of implementing each measure to each flight and the different elements that are used to compute it are stored in the Fig. ?? in descending order according to the cost values.

flightkey	measure	Cost	CPXdiff	CPXother	diffLevel	minDistAdepAdes	rerouteDist
17348307	LC	0,03790083	44,19	0	15	494489,1031	
17348307	RR	0,044257579	44,19	0			117,7
17348562	RR	0,044752741	43,69	0			117,7
17348166	RR	0,04575612	42,71	0			117,7
17348336	LC	0,046103325	36,15	0	15	494489,1031	
17348331	LC	0,046103325	36,15	0	15	494489,1031	
17348166	LC	0,046447272	42,71	0	15	787227,7216	
17348289	RR	0,049188392	39,66	0			117,7
17348573	LC	0,04994816	36,15	0	15	626196,9157	
17348305	RR	0,050087653	38,93	0			117,7
17348562	LC	0,050787831	43,69	0	15	1008067,164	
17348567	RR	0,051190171	38,07	0			117,7
17348383	RR	0,051190171	38,07	0			117,7
17348167	RR	0,052952078	36,77	0			117,7
17348289	LC	0,053386396	39,66	0	15	916763,9608	
17348305	LC	0,053813759	38,93	0	15	896563,2288	
17348331	RR	0,053835801	36,15	0			117,7
17348336	RR	0,053835801	36,15	0			117,7
17348573	RR	0,053835801	36,15	0			117,7
17349626	LC	0,05384277	30,81	0	15	494489,1031	
17348167	LC	0,054391956	36,77	0	15	809518,3249	
17348567	LC	0,055559019	38,07	0	15	916763,9608	
17348303	RR	0,0578369	33,58	0			117,7
17348263	RR	0,058910162	32,95	0			117,7
17348383	LC	0,059862391	38,07	0	15	1071798,05	
17348303	LC	0,062139486	33,58	0	15	896563,2288	
17349626	RR	0,06287331	30,81	0			117,7
17348234	RR	0,06287331	30,81	0			117,7
17348191	LC	0,06381291	25,84	0	15	494489,1031	
17348311	RR	0,064329366	30,09	0			117,7
17348306	RR	0,064956155	29,79	0			117,7
17348306	LC	0,066751744	29,79	0	35	494489,1031	
17348234	LC	0,067550563	30,81	0	15	896563,2288	
17348140	LC	0,068631552	21,46	0	5	494489,1031	
17348357	LC	0,068631552	21,46	0	5	494489,1031	
17348365	RR	0,06863418	28,14	0			117,7
17348263	LC	0,068890239	32,95	0	15	1071798,05	
17348191	RR	0,074515648	25,84	0			117,7
17348311	LC	0,074814486	30,09	0	15	1059957,224	
17348282	RR	0,081300813	23,6	0			117,7
17348066	LC	0,082616837	21,46	0	15	626196,9157	
17348282	LC	0,087348919	23,6	0	15	896563,2288	
17348365	LC	0,087783553	28,14	0	35	880789,7726	

17348357	RR	0,089047195	21,46	0			117,7
17348140	RR	0,089047195	21,46	0			117,7
17348066	RR	0,089047195	21,46	0			117,7
17347582	LC	0,089740408	18,63	0	15	539547,8436	
17349413	LC	0,092451785	12,75	0	5	217602,2693	
17348048	RR	0,09478673	20,1	0			117,7
17348136	RR	0,09569378	19,9	0			117,7
17348028	RR	0,09569378	19,9	0			117,7
17348412	RR	0,09569378	19,9	0			117,7
17348340	LC	0,09721445	16,2	0	5	628319,5693	
17348048	LC	0,097406929	20,1	0	35	494489,1031	
17348136	LC	0,098295894	19,9	0	15	809518,3249	
17348412	LC	0,098295894	19,9	0	15	809518,3249	
17348801	LC	0,099172689	15,51	0	15	424965,6463	
17348394	LC	0,100668595	17,24	0	45	217602,2693	
17347812	LC	0,10208775	15,18	0	45	86795,9648	
17348149	LC	0,107258622	16,3	0	15	626196,9157	
17348358	RR	0,108342362	17,46	0			117,7
17348028	LC	0,108598478	19,9	0	15	1008067,164	
17348358	LC	0,111337281	17,46	0	35	494489,1031	
17348239	RR	0,115606936	16,3	0			117,7
17348149	RR	0,115606936	16,3	0			117,7
17348239	LC	0,117353195	16,3	0	15	787227,7216	
17348213	LC	0,126195701	11,44	0	15	362755,1673	
17348387	RR	0,12755102	14,68	0			117,7
17347598	LC	0,131020885	13,18	0	15	628319,5693	
17348387	LC	0,141712954	14,68	0	15	964130,2732	
17347572	LC	0,143035803	10,69	0	5	628319,5693	
17348236	LC	0,144122974	13,18	0	25	628319,5693	
17347644	LC	0,147567606	11,59	0	15	628319,5693	
17347660	LC	0,148511283	11,51	0	15	628319,5693	
17347729	LC	0,153426926	11,1	0	45	231980,2833	
17347710	LC	0,16278797	11,62	0	15	809518,3249	
17348268	LC	0,179136201	12,6	0	35	787227,7216	
17347516	LC	0,184130441	9,09	0	15	628319,5693	
17347858	LC	0,19214817	11,83	0	35	809518,3249	
17348579	RR	0,193423598	9,34	0			117,7
17347800	LC	0,209025624	9,28	0	15	896563,2288	
17347517	LC	0,217041607	7,56	0	15	628319,5693	
17348326	LC	0,218151093	7,51	0	45	231980,2833	
17348403	RR	0,21905805	8,13	0			117,7
17348403	LC	0,243379969	8,13	0	15	964130,2732	
17348579	LC	0,251238281	9,34	0	55	626196,9157	
17347426	LC	0,265140328	8,81	0	55	628319,5693	

17348156	LC	0,272792283	3,66	0	5	217602,2693	
17347744	LC	0,279507628	6,07	0	15	737350,4533	
17347521	LC	0,295683207	6,54	0	35	628319,5693	
17348088	LC	0,303872961	5,2	0	25	494489,1031	
17348148	LC	0,304072425	9,37	0	85	625521,6075	
17347189	LC	0,320323475	4,8	0	15	628319,5693	
17348088	RR	0,322580645	5,2	0			117,7
17347728	RR	0,322580645	5,2	0			117,7
17348105	LC	0,377149219	3,92	0	15	626196,9157	
17349410	LC	0,404281751	3,86	0	35	424965,6463	
17348409	LC	0,405241443	4,96	0	45	628319,5693	
17348105	RR	0,406504065	3,92	0			117,7
17347728	LC	0,45540797	5,2	0	35	1084815,756	
17348421	LC	1,541464655	0	0	5	494489,1031	
17348275	LC	1,672088538	0	0	5	628319,5693	
17348467	LC	1,712738506	0	0	15	494489,1031	
17347845	LC	1,857876154	0	0	15	628319,5693	
17348264	RR	2	0	0			117,7
17348490	RR	2	0	0			117,7
17348467	RR	2	0	0			117,7
17348421	RR	2	0	0			117,7
17347780	LC	2,229451384	0	0	35	628319,5693	
17348367	LC	2,305151789	0	0	45	550234,4233	
17348264	LC	2,33882362	0	0	15	1071798,05	
17348490	LC	2,46526102	0	0	35	809518,3249	
17349322	LC	2,46526102	0	0	35	809518,3249	

Figure 15: Cost values for each flight and measure

The resulting benefits are then presented in the following sections through two different methodologies. The first presentation of the results is based on the improvement of the complexity situation in the overloaded sector. The complexity values are presented to assess the impact on this indicator every time a VSTAM measure is applied to a certain flight considering the minimum cost values. The results are then also presented in terms of the benefit in punctuality. For that, the punctuality indicators from the Performance Framework [23] are used.

5.1 Complexity results

To mitigate the overload presented in the initial complexity values of Fig. 14, the measures with the least amount of cost would be selected. The following figures represent the resulting complexity values once each flight is removed, both for the overloaded sector and the neighbouring sector that receives the flight.

The measure with the lowest cost value is a level-caping applied to the flight with code 17348307. The resulting complexity values both for the overloaded sector —LECMBLU— and the lower sector —LECMBLL— are represented in Fig. 16.

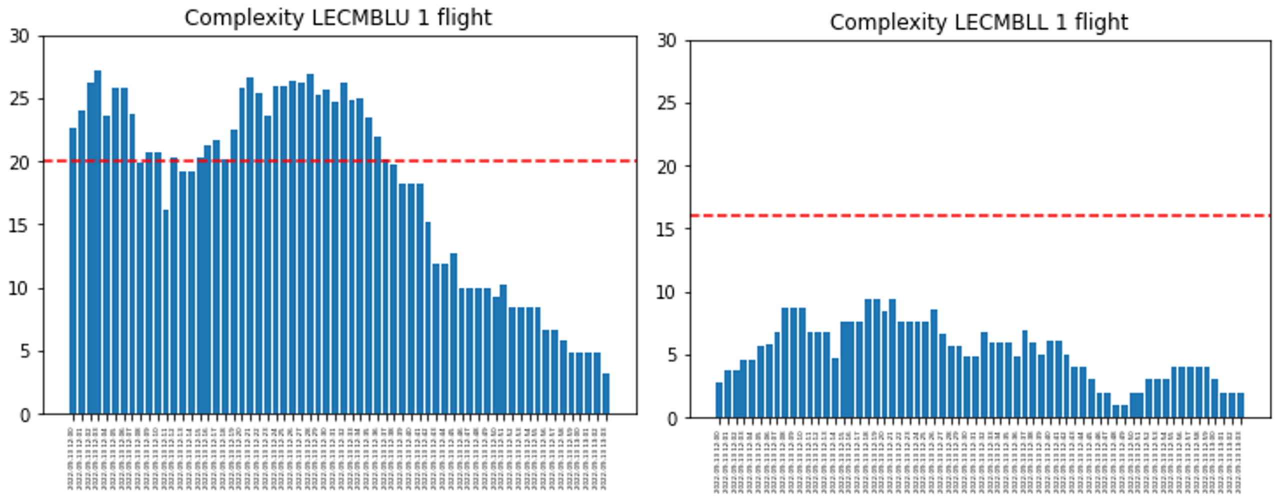


Figure 16: Complexity values after applying the first VSTAM measure

In this case, the complexity values for the overloaded sector are decreased in the second overload interval, while the lower sector could absorb even more traffic.

The second measure with the lowest cost value is a rerouting to the Asturias Upper sector applied to the flight with code 17348562. The resulting complexity values for both the overloaded sector —LECMBLU— and the lateral sector —LECMASU— are represented in Fig. 17.

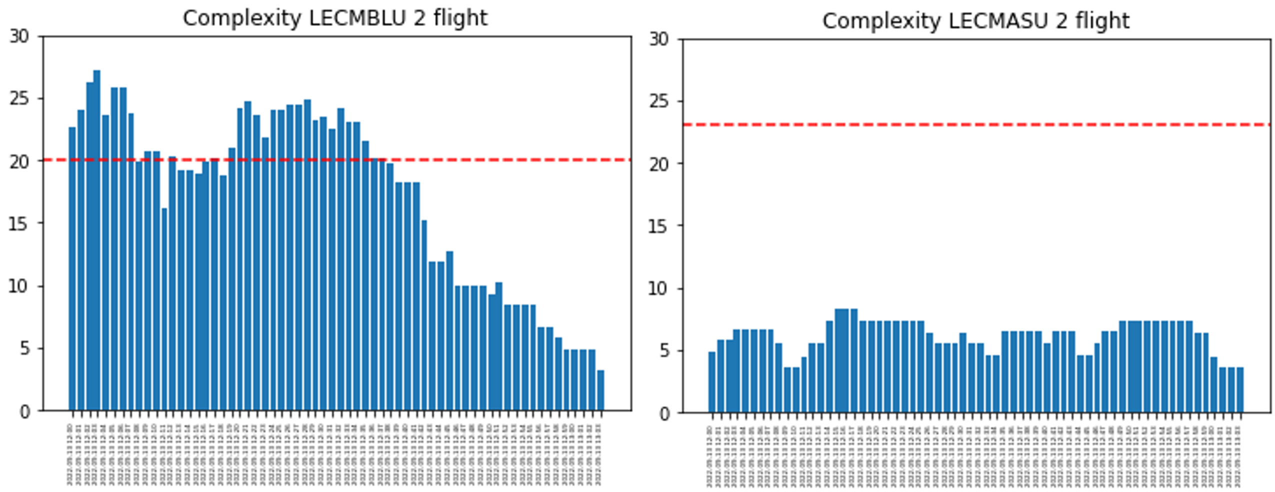


Figure 17: Complexity values after applying the second VSTAM measure

When removing the second flight from the overloaded sector, the second overloaded interval is further mitigated, and in time the lateral sector is able to absorb the flight and more.

The third measure with the lowest cost value is a rerouting to the Asturias Upper sector applied to the flight with code 17348166. The resulting complexity values both for the overloaded sector —LECMBLU— and the lateral sector —LECMASU— are represented in Fig. 18.

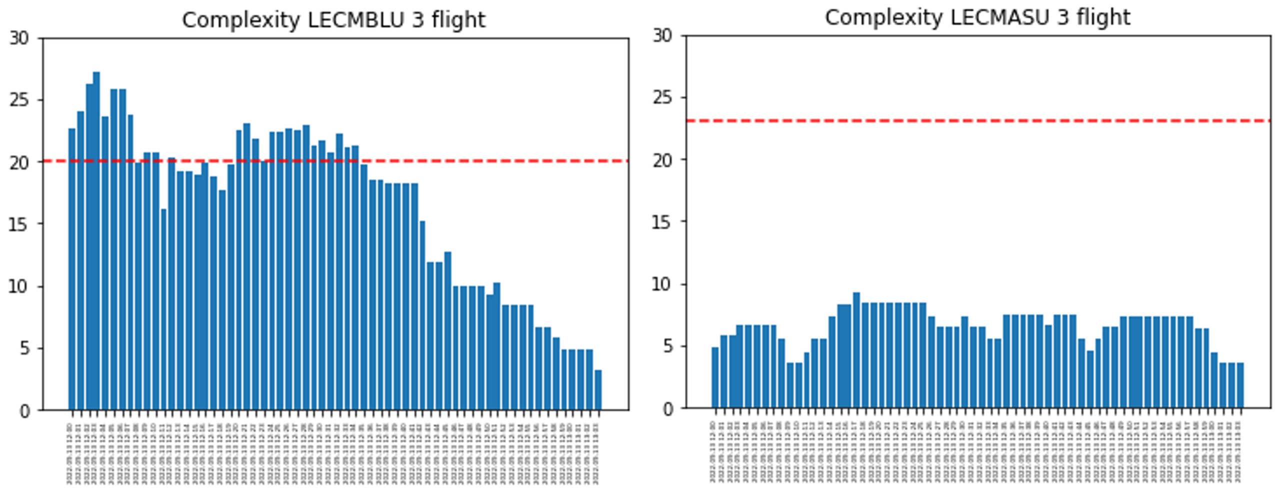


Figure 18: Complexity values after applying the third VSTAM measure

As in the previous case, the complexity values in the second overloaded interval are decreased and the Asturias upper sector is not even near its threshold of capacity, so it could absorb even more flights from the overloaded sector.

The fourth measure with the lowest cost value is a level capping to the lower sector applied to the flight with code 17348336. The resulting complexity values for both the overloaded sector and the lower sector are represented in Fig. 19.

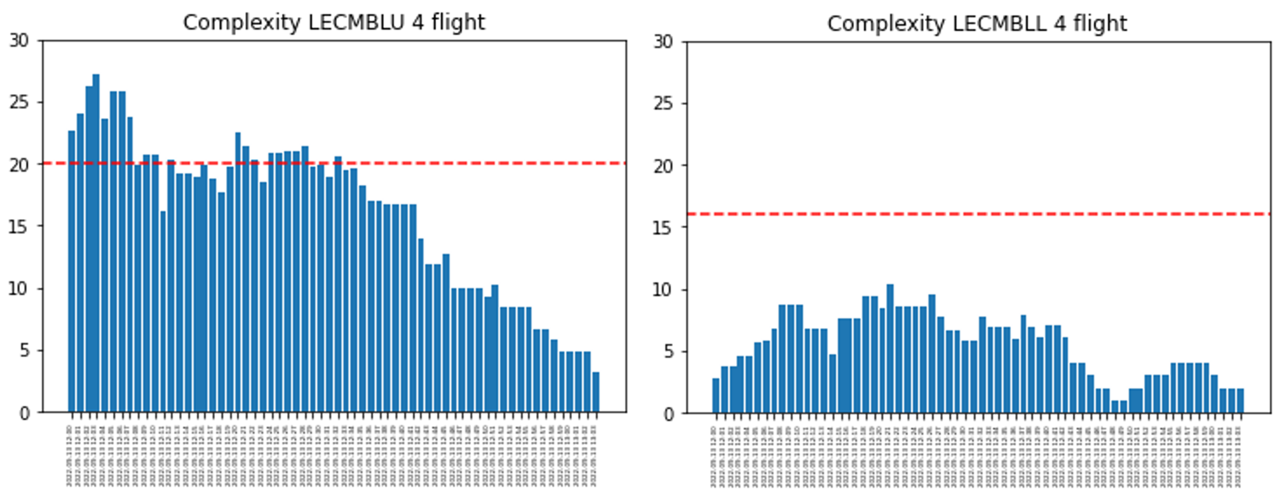


Figure 19: Complexity values after applying the fourth VSTAM measure

With the removal of the third and fourth flights, a tendency can be noticed. Although the complexity values for the second overloaded period have been leveled, the first peak of demand remains unchanged.

5.2 Performance results

Aside from the improvement in complexity values with respect to the thresholds defined, the benefits of applying this cost function to the overloaded sector can also be defined in terms of other indicators. To determine which indicators to use, the Performance Framework [23] has been referenced.

In particular, punctuality metrics have been selected as appropriate to express the amount of delay spared and the improvement of the accuracy of traffic demand prediction. The identified indicators to measure are described in Table 4.

KPIs / PIs	Unit	Description
PUN1 Average departure delay per flight	min/flight	Average delay (AOBT – SOBT) per flight.
PUN2 % Flights departing within +/- 3 minutes of scheduled departure time	%	% Departures with —AOBT – SOBT— +/- 3 min. The difference in Actual Departure Time vs. Scheduled Time
PUN3 % Flights departing within +/- 5 minutes of scheduled departure time	%	% Departures with —AOBT – SOBT— +/- 5 min. The difference in Actual Departure Time vs. Scheduled Time
PUN4 % Flights departing within +/- 10 minutes of scheduled departure time	%	% Departures with —AOBT – SOBT— +/- 10 min. The difference in Actual Departure Time vs. Scheduled Time
PUN5 % Flights departing within +/- 15 minutes of scheduled departure time	%	% Departures with —AOBT – SOBT— +/- 15 min. The difference in Actual Departure Time vs. Scheduled Time

Table 4: Punctuality Indicators

These indicators will be computed for two different cases in order to identify the benefits of implementing the cost function: the reference scenario and the solution scenario. The reference scenario would be the one in which the ATFCM regulation was applied to the sector. In this case, the actual departure times would be considered as the real take-off times.

On the other hand, the solution scenario would be the one in which there was no ATFCM regulation and the necessary VSTAM measures would be applied to certain flights —taking into account the ones with the minimum values of the cost function. The actual departure times would be considered to be the estimated take-off times (ETOT) according to the last flight plan issued at T0-60'. For both scenarios, the scheduled departure time is considered to be the first ETOT filed in the flight plan.

It should be noted that information about the updates in ETOT information in the different flight plans issued was only available for those flights with a Spanish departure airport. However, this should not be an issue, as the main flights affected by such delay variances should be those that had not yet departed at the time of VSTAM application.

Table 6 represents the departure times of all flights with available ETOT update information, as well as the delay values in minutes.

Flightkey	Flight Plan Update Instant	ETOT Reference	ATOT Reference	Delay (min)
17347517	2022-09-13 10:55	2022-09-13 10:30	2022-09-13 10:53	23
17347521	2022-09-13 10:06	2022-09-13 10:30	2022-09-13 11	30
17348801	2022-09-13 10:29	2022-09-13 11:05	2022-09-13 11:21	16
17347582	2022-09-13 10:07	2022-09-13 10:35	2022-09-13 11:05	30
17347516	2022-09-13 10:23	2022-09-13 10:30	2022-09-13 11:11	41
17347572	2022-09-13 10:06	2022-09-13 10:40	2022-09-13 11:29	49
17348148	2022-09-13 10:06	2022-09-13 10:32	2022-09-13 11:01	29
17349413	2022-09-13 07:35	2022-09-13 11:51	2022-09-13 11:56	5
17347644	2022-09-13 10:06	2022-09-13 10:50	2022-09-13 11:22	32
17347660	2022-09-13 10:11	2022-09-13 10:55	2022-09-13 11:27	32
17347598	2022-09-13 10:06	2022-09-13 10:45	2022-09-13 11:20	35
17348340	2022-09-13 04:39	2022-09-13 11:20	2022-09-13 12:04	44
17347812	2022-09-13 10:11	2022-09-13 11:15	2022-09-13 11:15	0
17347426	2022-09-13 10:49	2022-09-13 10:15	2022-09-13 11:31	76
17347189	2022-09-13 10:45	2022-09-13 9:40	2022-09-13 12:13	153
17349410	2022-09-13 10:14	2022-09-13 11:55	2022-09-13 11:58	3
17347780	2022-09-13 10:54	2022-09-13 11:15	2022-09-13 11:47	32
17347845	2022-09-13 10:54	2022-09-13 11:25	2022-09-13 11:55	30

Table 6: ETOT vs. ATOT values for the reference scenario

The departure times for this sample of flights in the reference scenario make up a mean delay of 36.67 minutes per flight and indicate that more than 80% of the flights were delayed in this particular case.

Table 8 indicates the departure times of the flights in the sample with available ETOT update information, as well as the predicted delay values in minutes.

Flightkey	Flight Plan Update Instant	ETOT Solution	ATOT Solution	Delay (min)
17347517	2022-09-13 10:55	2022-09-13 10:30	2022-09-13 10:53	0
17347521	2022-09-13 10:06	2022-09-13 10:30	2022-09-13 10:30	30
17348801	2022-09-13 10:29	2022-09-13 11:05	2022-09-13 11:24	0
17347582	2022-09-13 10:07	2022-09-13 10:35	2022-09-13 10:51	14
17347516	2022-09-13 10:23	2022-09-13 10:30	2022-09-13 11:05	6
17347572	2022-09-13 10:06	2022-09-13 10:40	2022-09-13 11:12	17
17348148	2022-09-13 10:06	2022-09-13 10:32	2022-09-13 10:32	29
17349413	2022-09-13 07:35	2022-09-13 11:51	2022-09-13 11:51	55
17347644	2022-09-13 10:06	2022-09-13 10:50	2022-09-13 11:15	7
17347660	2022-09-13 10:11	2022-09-13 10:55	2022-09-13 11:16	11
17347598	2022-09-13 10:06	2022-09-13 10:45	2022-09-13 11:18	2
17348340	2022-09-13 04:39	2022-09-13 11:20	2022-09-13 11:55	9
17347812	2022-09-13 10:11	2022-09-13 11:15	2022-09-13 11:15	0
17347426	2022-09-13 10:49	2022-09-13 10:15	2022-09-13 11:30	1
17347189	2022-09-13 10:45	2022-09-13 9:40	2022-09-13 11:37	36
17349410	2022-09-13 10:14	2022-09-13 11:55	2022-09-13 11:58	0
17347780	2022-09-13 10:54	2022-09-13 11:15	2022-09-13 11:47	0
17347845	2022-09-13 10:54	2022-09-13 11:25	2022-09-13 11:54	1

Table 8: ETOT vs. ATOT values for the solution scenario

In this case, the delay values have been mostly decreased. In particular, the resulting mean delay is 9.16 minutes per flight. Considering that any delay of more than 15 minutes at take-off is considered a delayed flight, only 22% of flights would have been delayed.

With these delay values, the indicators defined in Table 4 can be computed and compared between the reference and solution scenarios. The results of these computations can be found and compared in Table 10.

KPI	Reference Value	Solution Value	Variation
PUN1	36.67 min/flight	9.17min/flight	-75%
PUN2	89% flights delayed +3min	56% flights delayed +3min	-38%
PUN3	83% flights delayed +5min	50% flights delayed +5min	-40%
PUN4	83% flights delayed +10min	33% flights delayed +10min	-60%
PUN5	83% flights delayed +15min	22% flights delayed +15min	-73%

Table 10: Punctuality indicators comparison

The values of all the defined punctuality indicators present a decrease between the reference and the solution scenarios. While the reference scenario presents a mean delay of 36.67 minutes per flight, the solution scenario is able to reduce it to a little more than 9 minutes, representing a variation in the indicator of -75%. In terms of percentage of delayed flights, all the related indicators present a decrease in that aspect, with a variation ranging between -38% and -73% depending on the amount of delayed considered.

Conclusions and Future work

This thesis presents the definition of a mathematical model to represent the cost of implementing a certain VSTAM measure to a given flight in order to solve a particular DCB imbalance in the near future. The VSTAM measures considered are level-caping and rerouting. This cost is then used to provide a ranking of measures considering minimum cost values that could be applied to solve that overload.

The described cost is based both on the potential resolution of the overload from the air traffic control point of view and on the impact on the flight to which the measure would be applied. The first element is defined as the impact on the complexity values —computed with the eCOMMET tool— for the overloaded sector and the neighbouring sector which would be receiving this flight. The second element is defined depending on the type of measure to be applied. In the case of level-caping measures, the RFL and the distance to the origin and destination airports are considered, while for the rerouting, the main element is the additional distance flown.

To validate this approach, the algorithm developed is tested by simulation. One use case in one sector of the Madrid ACC is selected to define the cost values for the flights expected to be in it 60 minutes before the operation. A particularly overloaded interval is identified for the sector LECMBLU on September 13th, 2022 between 12:00 and 13:00. The resulting benefits of applying the cost function for optimising the flight selection in this particular imbalance are measured in terms of complexity and punctuality.

Results of this use case show that overloaded periods are improved in terms of complexity. Flights that were planned to be included in these intervals are the ones with the minimum cost for implementing a measure. In addition, measures are presented quite balanced, reflecting that the two sectors available for acquiring the exceeding traffic were able to do so. However, results also show that the improvements on complexity tend to focus on the overloads with most duration and small to medium peaks tend to be overlooked.

Concerning the punctuality results, five key performance indicators from the Performance Framework in SESAR have been selected. The first indicator is the average delay per flight, which is measured in terms of the difference between the ATOT and ETOT. The implementation of the cost function presents an improvement on this indicator by 75%. The second, third, fourth, and fifth indicators are related to the percentage of flights with a given delay which ranges from 3 to 15 minutes. These indicators all present a decrease ranging from 38% to 73%. These improvements in punctuality are related to the fact that the sector had to be regulated in order to solve the imbalance. The delays avoided by using this cost function are related to the flights that had not yet departed at the time of the VSTAM application.

All in all, while the developed mathematical model has shown promise in addressing demand-capacity imbalances through the application of Very Short-Term ATFCM Measures (VSTAM), it is important to acknowledge certain limitations that warrant consideration. Firstly, the model does not explicitly address the uncertainty associated with non-nominal operations, which could impact its ability to accurately predict the impact of VSTAM measures on air traffic flow. Further discussions will be held in order to determine how the model reacts to non-nominal situations enhancing the comprehensiveness of the model.

Moreover, additional evaluations of the model's precision in predicting the impact of VSTAM measures on air traffic flow will be carried out in the near future. Recognizing the potential limitations in the model's ability to precisely forecast the effects of VSTAM measures on traffic flow is crucial for ensuring a realistic assessment of its applicability. Addressing these limitations could involve further research into refining the model's algorithms to account for uncertainties and enhancing its predictive capabilities. Moreover, exploring the integration of real-time data and adaptive mechanisms within the model could potentially mitigate these limitations and improve its accuracy in predicting the impact of VSTAM measures on air traffic flow. These considerations will be vital for advancing the model's effectiveness and applicability in addressing demand-capacity imbalances in air traffic management.

The development of this mathematical model for VSTAM selection has been carried out within the DCB solvers feature of the validation LTM tool developed in CRIDA. Further work will involve the integration of this model into a whole optimisation framework so that the result could be what measures to apply to solve all overloads on a given period. At the moment, one of the current lines of research within this project is to implement other types of measures and to allow the modification of the weights each element of the cost function has on the overall value, so as to favour one measure over the others.

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Annex I

This annex contains an example of an input file for complexity computation.


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