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A STAM Model Based on Spatiotemporal Airspace Sector Interdependencies to Minimize Tactical Flow Management Regulations

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Abstract: The lack of airspace capacity poses a significant challenge for a sustainable air transport system, particularly in scenarios of future growing demand. Air traffic management digitalization opens pathways for innovative and efficient solutions to tackle existing inefficiencies arising from spatially fragmented airspace. While research has focused on digitalized ATM services to improve airspace capacity, synergies among adjacent sectors to utilize latent capacity remain unexplored. Using a sector network model, in this study, we analyze spatiotemporal sector interdependencies, quantify time-stamp topological interdependencies, and evaluate capacity enhancement possibilities for sectors unable to meet dynamic demand. The occupancy count dynamic evolution and poor correlation among the over-loaded sectors with the occupancy count of its adjacent sectors provide opportunities for a short-term ATM mechanism, ensuring sector-level capacity invulnerability and enhancing airspace capacity at the network level. A computational experiment using real data from the European airspace is carried out to illustrate and validate this innovative solution.

Keywords: airspace capacity; demand–capacity balance; early handover; sector occupancy; STAM; sustainable air transport

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1. Introduction

During the first semester of 2023, air traffic in the European airspace was subject to an average of 9.58% en-route flight regulations [1]. The predicted traffic demand increment will have a negative impact on the amount of en-route flight regulations if the conventional sectorized air traffic control (ATC) concept is not adapted with new strategies to manage future air traffic volumes.

Several reports, such as [2], advocate for new solutions since traffic demand increments push the system toward air traffic management (ATM) capacity limits. In fact, the Single European Sky (SES) initiative was launched by the European Commission to improve the quality of ATM services. However, the tight interdependencies among ATM services [3] and the trade-offs among the ATM key performance areas (KPAs) considerably increase the difficulties in identifying innovative solutions that can improve particular key performance indicators (KPIs), such as en-route air traffic flow management (ATFM) delays, without negatively impacting other KPIs related to safety, capacity, environment, and cost-efficient KPAs.

While regulations can negatively impact aircraft operators (AOs), the airspace community recognizes them as a last-resort, albeit inefficient, solution for addressing overloaded sector issues on the operation day. These regulations serve as essential mechanisms for restoring air traffic flow and capacity management (ATFCM) stability in response to real-time events that lead to overloaded traffic volumes.

Airspace is structured into elementary sectors with well-defined lateral and vertical dimensions, which can collapse with other elementary sectors to form operational sectors, serving as the elementary capacity reference of the ATM system. Sector capacity is understood as the maximum number of flights that may enter a sector per hour averaged over a sustainable period of time (e.g., 3 h), ensuring safe, orderly, and efficient traffic flow [4]. On the operation day, depending on the traffic pattern, staffing, weather conditions, and technical problems, a monitoring value is declared, which represents the maximum number of flights per hour that can enter a sector before an ATFM regulation becomes necessary.

Macroscopic approaches are usually applied to wide geographical areas, providing corrective measures before the aircraft flies. They use aggregated flight plans as the input, and the ATC sector and airport capacities as the 'limiting factor'. Demand capacity balancing (DCB) tools have been developed for strategic ATFCM, based on aggregated flight plans, with the ATC sector and airport capacities as 'limiting factor'. DCB approaches provide good results to ATFCM problems, addressing large-scale scenarios [5,6]; however, they do not account for the day-of-operation events that impact the workload of the air traffic controllers (ATCos). SESAR has proposed enhancing DCB to dynamic DCB (dDCB) at a tactical level by implementing a set of short-term air traffic flow and capacity management measures (STAMs) [7]. To improve tactical capacity management procedures and optimize traffic throughput, several initiatives, such as iACM, have been tested to estimate the sector capacity, integrating the management of multiple KPIs, such as the controller workload (WL) and sector occupancy [8]. Although it is well accepted that ATC WL is the main hard constraint to sector capacity, there is no consensus as yet on how ATC WL can be estimated since the WLs of main airspace actors (i.e., ATC and pilots) at the operational level [9] are related to various factors that can be qualitative and quantitative [10,11].

In this context, we propose a STAM mechanism. We consider the ability of network capacity to shift the ATC WL among adjacent sectors by applying an early handover mechanism to conflict-free aircraft located near the exit waypoint. The main contributions are described next. First, the novel methodology is presented. Secondly, a comprehensive set of computational experiments is carried out to illustrate and validate the proposed approach. These experiments draw from real, up-to-date data from the European airspace. Maps, time-series plots, and occupancy correlation analyses are used to identify sectors of interest and uncover valuable insights into spatiotemporal interdependencies among adjacent sectors. Furthermore, a simulation is conducted to delve into the implications of implementing the early handover mechanism, thereby deepening our understanding of its effects.

The rest of the paper is structured as follows. Section 2 outlines the ATM capacity regulation mechanism; Section 3 offers formal definitions of the STAMs. Subsequently, in Section 4, we delve into the current state of the art. The materials and methods used are presented in Section 5. In Section 6, we explain the set of computational experiments carried out, covering a descriptive analysis of the data, analysis of correlations, and the dwell time of trajectories. A comprehensive discussion of the results is offered in Section 7. Finally, Section 8 presents the main conclusions of this work and identifies future research.

2. Understanding the ATM Capacity Regulation Mechanism

ATM consists of three main layers: air space management (ASM), air traffic services (ATS) and air traffic flow, and air traffic control management (ATFCM); the purpose of the latter is to avert the overloading of portions of the airspace while ensuring that the capacity is fully exploited, which is crucial in dense and busy airspace [12].

The main actors of ATFCM are the network manager (NM) and flow management positions (FMPs) delegated by area control centers (ACCs), which interact through a collaborative decision-making process enhanced via different supporting tools, such as OPTICON [12], which helps with the selection of the sector configuration. Both actors can run ATFCM simulations to evaluate a set of capacity constraints in terms of the total delay generated, delay distribution, and individual delay generated by each capacity constraint, in order to determine the best measure to use with consensus, with the rest of the FMPs, AOs, affected military authorities, and airport authorities.

Considering the importance of the dwell time to implement ATFCM demand/capacity balance measures and the inherent uncertainty to traffic demand, the ATFCM tasks are grouped into three temporal phases in a rolling time horizon [12].

- Strategic flow management: This process takes place seven days or more prior to the operation day (D), with the main focus on collecting data for the early identification of major demand/capacity imbalances, such as shows, major sports events, and military exercises. Regarding imbalances, the NM generates the network operations plan (NOP) to optimize available airspace capacity. Measures that are simulated to generate the NOP include level capping scenarios, diverting flows to off-load 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 analyze the traffic demand for the day of the operation, propose the necessary adjustments to the NOP, harmonize the demand and capacity, and ensure the cost-efficient use of the 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), negotiating extra capacity (monitoring values, occupancy counts), ATFCM/ASM (civil/military coordination), reducing traffic complexity, holding the pattern, and regulating the demand.

  The agreed-upon measures between the NM and FMP are formalized in the ATFCM daily plan (ADP), which covers a 24-h period for each day, starting as a draft on D-2 and finalized on D-1. During tactical operations, the ADP is further modified according to the developments of the day [12].
- Tactical flow management: This process takes place on the operation day (D) to analyze, in real time, events that affect the ADP; it proposes the necessary ADP modifications to solve the demand/capacity imbalances. Despite there being several causes that may require ADP adjustments (e.g., staffing problems, significant meteorological phenomena, crises), the most reported cause is "ATC Capacity", which includes any unexpected limitation related to air infrastructure. Note that "ATC Disruptions" reported by DSNA (French air navigation service provider, https://dsna.fr/, accessed on 1 July 2023) in the EUROCONTROL balanced scorecard (https://www.eurocontrol.int/Economics/BalancedScorecard.html#, accessed on 1 July 2023) for the period January–May 2023 is higher than the "ATC Capacity", but it is considered an exception due to French ATC strikes.

  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-pick 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 about the sector configurations and activations (pre-tactical and tactical phases), traffic volume, the monitoring values of traffic volume, and information about events that will impact the capacity at an aerodrome or ACC.

Figure 1 illustrates the different ATFCM phases. As can be observed, the ADP can be constantly updated during the operation day to respond to a new situation triggered by a change either in the traffic demand or ATC system capacity.

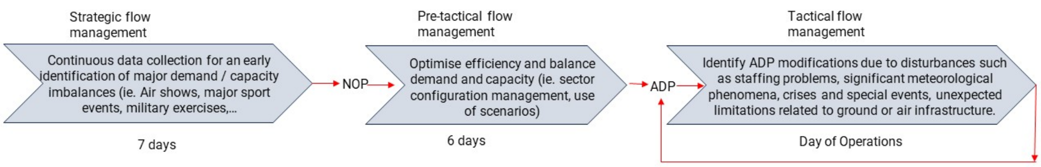


Figure 1. Scheme of the different ATFCM phases.

3. STAMs

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

On the operation day, the dDCB 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 to address 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 both flights in the execution phase and ground operations.

3.1. Description of the Main STAMs

Here, we present a synopsis of the key STAMs [13].

- 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. It primarily focuses on en-route sectors and provides the flexibility to dynamically adjust the sector capacity, whether it requires an increase or decrease. By leveraging the available resources (e.g., ATCos), weather prediction, and incoming traffic flow, this service facilitates efficient and 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 (ATC TWR). This service plays a vital role as one of the primary actions within the STAMs to reduce the workload of ATCos in terminal maneuvering area (TMA) sectors. By strategically spacing out departure times, the dDCB service helps optimize the aircraft flow and reduces congestion in TMAs, ensuring a more efficient and manageable workload for ATCos.
- Miles-in-trail: En-route radar ATCos have the ability to activate a service that addresses separation minima infringements among aircraft flying at the same flight level. By instructing individual aircraft to maintain the same speed or Mach number, controllers can effectively prevent these infringements. This service, which is categorized as a dDCB measure, plays a significant role in reducing the workload of ATCos.

- SID STAM: The ATC TWR has the ability to make a slight adjustment to the planned standard instrument 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, optimizing airspace utilization and minimizing disruptions. By utilizing this method, the ATC TWR 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 ATCFM by identifying, assessing, and facilitating slot swapping for eligible flights. The aim is to minimize 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 slot swapping, the service helps optimize the utilization of available resources and reduce disruptions caused by delays.

In spite of the advantages offered by STAM services, there remains the issue of unbalanced capacity among neighboring sectors, resulting in a latent capacity that needs to be addressed with a more agile approach. This disparity between the planned entry time and predicted entry time of flights en-route requires attention.

To tackle this problem, this paper introduces a novel mechanism that employs a causal model for an early handover procedure, effectively offloading an overloaded sector. By doing so, the mechanism mitigates the inefficiencies caused by rerouting or ground delays. As a result, a promising opportunity arises for enhanced collaboration among adjacent sectors, leading to an overall increase in the capacity of the sector network.

3.2. Functional Requirements of a STAM

The requirements for a STAM may vary depending on the specific context and goals of the measure. However, the following are some common requirements that STAMs should typically meet (inspired by [14]).

1. Effectiveness: STAMs should be effective at managing and optimizing air traffic flow. It should lead to improved efficiency, reduced delays, and increased capacity in the airspace.
2. Safety: STAMs must not compromise or negatively impact the safety of flights or air traffic operations.
3. Local: A measure applied within a specific sector should not have negative effects (such as delays) that are downstream-propagated to subsequent sectors.
4. Scalability: The measures should be scalable to handle different levels of air traffic and accommodate future growth in air travel.
5. Flexibility: Air traffic conditions can change rapidly, so STAMs should be adaptable to handle varying situations and demands.
6. Minimization of environmental impacts: STAMs should aim to minimize the environmental impacts of air traffic operations, e.g., by reducing fuel consumption and emissions.
7. Integration with existing systems: STAMs should be able to integrate seamlessly with existing air traffic management systems and procedures.
8. Cost-effectiveness: The benefits of implementing STAMs should outweigh the associated costs.
9. Agile collaboration and coordination: STAMs often require collaboration and coordination between different stakeholders, including air traffic control, airlines, airports, and relevant authorities.
10. Real-time data and analysis: The measures should utilize real-time data and analyses to make informed decisions and adjustments to air traffic flow.
11. Risk assessment: Before implementation, a thorough risk assessment should be conducted to identify potential risks and mitigation strategies.

12. Compliance with regulations: STAMs must comply with aviation regulations and standards set by relevant authorities.
13. User-friendly interfaces: If STAMs involve new technologies or tools, user interfaces should be intuitive and user-friendly.

3.3. Assessing a STAM to Avoid Overcapacity

This paper introduces a novel mechanism to calculate the dynamic evolution of sector occupancy and to prevent overcapacity by coordinating the physical entry of a new aircraft with the virtual exit of another aircraft.

A straightforward and coherent approach is to use speed regulation to delay the entry time of one aircraft while coordinating it with the speed regulation for the early exit of another aircraft. While this method is relatively simple to implement for specific pairs of entry/exit aircraft, it does come with several drawbacks:

- Performance impact: Airspace users typically determine their cruise speed based on the cost index of the company. Any deviation from the cost index speed will lead to increased fuel consumption and higher costs.
- Delays: Applying delays to the entry time of an aircraft affects downstream sectors and the TMA. Although this delay can be partially mitigated by allowing the aircraft to speed up in the sector under consideration, it still negatively impacts the overall performance.
- Scale: If the overloaded sector is not solely due to one aircraft but rather a consequence of increased traffic, managing the slowdown of several aircraft while simultaneously speeding up others can introduce safety and performance concerns. Additionally, such a scenario could significantly increase the workload for ATCos as they attempt to coordinate numerous speed change instructions.

This mechanism fails to fulfill various functional requirements, including:

- Local: Delays imposed on an entry aircraft are transmitted downstream to subsequent sectors, potentially causing a ripple effect of delays in the airspace.
- Agile collaboration and coordination: The approach necessitates coordination among multiple pilots, each with their own reaction delay to ATC instructions, which can complicate and slow down the process.
- Cost-effectiveness: Any speed adjustments made in relation to the airline's cost index will result in a cost penalty.
- Effectiveness: Altering the speed of an aircraft, either speeding up or slowing down, can lead to conflicts that require additional ATC instructions, such as changes in heading, which directly impacts sector occupancy and overall efficiency.

To overcome those drawbacks, a novel early handover mechanism that fulfills these four requirements is presented in Section 5.4.

4. State of the Art

As mentioned in the introduction, WL constitutes the primary constraint on sector capacity, yet there is no consensus on how ATC WL can be estimated. Among the different WL estimators, EUROCONTROL developed an abacus to map the sector occupancy count with the instant WL rate [15] using COCA WL concepts [16]. In the operational context of ATFCM, these relationship abacuses are employed strategically for each specific sector. They determine the monitoring values used during the tactical phase to issue warnings or assess the risk, considering the sector occupancy.

In [17], the COPTRA approach proposes a new algorithm to improve the estimation of the occupancy count by reducing the estimation to a 1 min interval, to better support STAM. Regardless of the better estimation accuracy achieved, the error—with respect to the real occupancy—cannot be used to design a tactical mechanism that would avoid under-capacity or over-capacity based on sector occupancy.

Among the different alternatives that attempt to shift capacity to where it is most needed, there are three approaches that provide the baseline for a flexible, dynamic, and adaptable airspace configuration:

- Dynamic airspace configuration (DAC): Analyzes how to dynamically reconfigure airspace [18], in response to demand fluctuations, adverse weather, and the limitations of human cognition, by combining predefined sectors (merging and dividing) to meet current airspace requirements. Different models [19] have been developed to describe the airspace (cell model, flight trajectory model, Voronoi diagram model, and graph model), with each one supporting different optimization algorithms to partition the airspace into sectors. In [20], a comparison of eight methods using three-configuration airspace solutions with projected simulated flight tracks in the Kansas City Center offers insight into the ATFM delay reduction achievable by implementing DAC.
- Dynamic airspace sectorization (DAS): Although it also targets the dynamic airspace reconfiguration as DAC, it considers a continuous airspace rather than predefined airspace blocks. DAS is an innovative approach that changes the classical concept "flow follows structure" to a new concept "structure follows flow", where the airspace structure is dynamically adjusted to the traffic flow [21].
- Flight-centric air traffic control (FCA): Similar to DAS, it eliminates sector boundaries, resulting in a single, consolidated airspace where multiple controllers each manage a designated number of aircraft [22]. Although FCA is less developed with respect to DAC and DAS, there are some approaches that attempt to support FCA that rely on DAS. For instance, Ref. [23] proposed an airspace sectorization that does not rely on explicit expertise from ATCos. Instead, it leans toward a more flight-centered sectorization, where the sectorization structure is heavily influenced by predicted traffic.

Regardless of the promising benefits that could be achieved, all three approaches rely on the quality of traffic prediction to propose different potential ATFCM sectorizations at strategic phase and adjust parameters at the tactical phase.

This paper introduces a novel STAM mechanism that amalgamates the key advantages of the DAC and DAS approaches while circumventing their drawbacks. The DAC approach excels at providing a means to balance WL among adjacent sectors, thereby preventing overloaded or underloaded scenarios. However, it suffers from incurring substantial transitional costs and it requires meticulous planning when implementing tactical airspace modifications. On the other hand, the DAS approach's strength lies in its alignment of airspace structures with traffic flows. Yet, it is burdened by the cost-inefficiency of retraining ATCos for new volumes and flows, as well as the development of new control work position (CWP) services.

Our proposed early handover mechanism relies on a spatiotemporal analysis of sector occupancy interdependencies to balance ATC WL among adjacent sectors at the operational level. It achieves this by making slight adjustments (in terms of space and time) to sector boundaries, thus avoiding transitional costs. This methodology offers a swift and efficient means of mitigating peak occupancy values that may arise due to disparities between planned and airborne trajectories on the operation day.

5. Materials and Methods

This section encompasses the materials and methodologies employed, divided into the subsequent subsections: raw data, software, data preprocessing, and the proposed approach (the early handover mechanism).

5.1. Raw Data

Air traffic data were obtained from *the OpenSky Network* (http://www.opensky-network.org, accessed on 1 July 2023) [24], a non-profit association that aims to improve the security, reliability, and efficiency of air space usage by providing open-access, real-world air traffic control data to the public. The data pertain to European sectors from 23 September 2022.

In the European airspace, over 30,000 flights take to the skies each day [25], which constitutes a substantial volume of air traffic. To effectively manage this high influx of flights, the sectors are meticulously configured for optimal efficiency. As part of the current study, it has been shown that the European airspace can be fragmented into 7581 sectors (see Figure 2), which can be dynamically set up from 9126 distinct airblocks. Each sector is equipped with specific configurations tailored to its operational requirements. This study focuses on those sectors positioned above 180 FL, as they play a crucial role in handling significant portions of both ascending and descending air traffic, including traffic flows during the cruise phase.

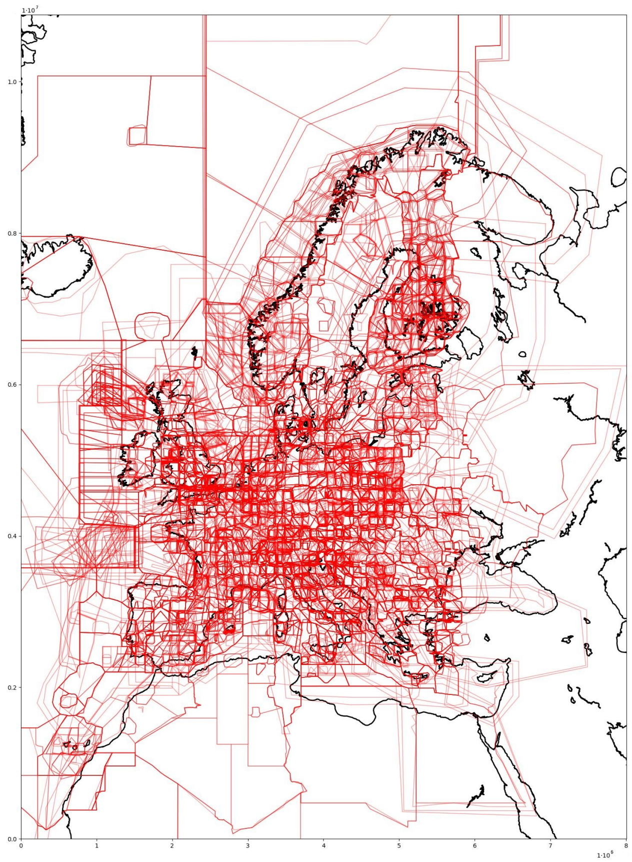


Figure 2. European airspace map with sector boundaries highlighted in red (date: 23 September 2022).

Data on airblocks, sectors, opening schemes, and traffic patterns were collected (see Figure 3). Afterward, an analysis of sector occupancy was conducted, carefully taking into account the selected day's specific configurations and the prevailing traffic flow during different hours.

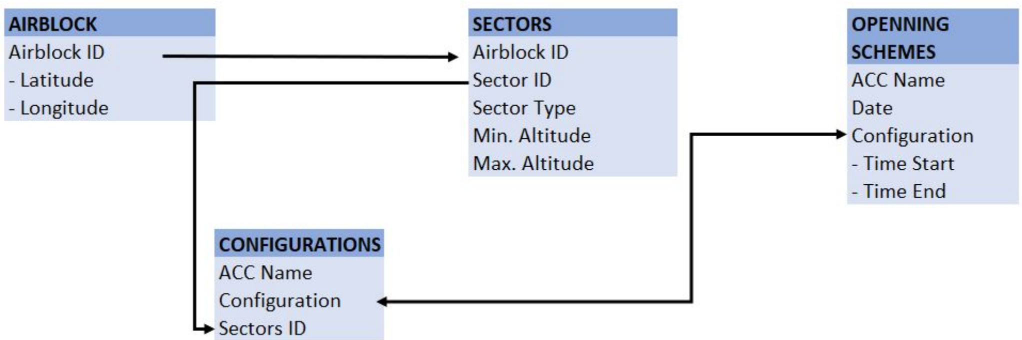


Figure 3. Representation of the dataset used.

For a comprehensive assessment of the airspace utilization in the European region, the dataset collated for this paper is confined to a single day with 29,685 flights, ensuring that only larger commercial aircraft, excluding drones and small planes, which have never exceeded the 180 FL level, are considered.

5.2. Software

Python 3.11 [26] was used to analyze data and carry out the computational experiments. Python is a high-level, interpreted programming language known for its simplicity and readability. It supports various programming paradigms, including object-oriented, functional, and imperative styles, making it versatile and widely used across different domains. There are applications in a wide range of fields, including data analysis, artificial intelligence, scientific research, and web development. With its user-friendly nature and vast community support, Python has gained massive popularity, becoming one of the most widely used programming languages for both beginners and experienced developers. The proactive Python community continuously contributes to the language's growth by creating new libraries, updating existing ones, and providing extensive documentation and tutorials. The main packages employed are *matplotlib* [27] (to create visualizations), *numpy* [28] (to perform mathematical operations on arrays), *pandas* [29] (to analyze, clean, explore, and manipulate data), *scipy* [30] (for scientific computing and technical computing), and *shapely* [31] (for the manipulation and analysis of planar geometric objects).

Bluesky ATM offers simulation capabilities that enable users to create and manipulate virtual flight data for research, analysis, and testing purposes. This simulation functionality allows users to generate artificial flight data points, replicating aircraft movements, positions, and attributes. These simulated data points can be integrated into *Bluesky*, alongside real-time data, creating a comprehensive dataset. The main simulation capabilities are described next.

- Virtual aircraft creation: Users can define simulated aircraft with attributes such as unique identifiers, call signs, origin countries, positions, altitudes, velocities, and headings.
- Time-based simulation: The simulation process incorporates timestamps to provide a time-varying representation of aircraft movements.
- Customized scenarios: Researchers and analysts can design customized scenarios for testing aviation-related systems, evaluating ATM strategies, studying airspace utilization, and more.
- Multi-user interaction: Simulated data points generated by one user can be accessed by other users in real time, promoting collaboration.

There are several applications, such as research and development (e.g., researchers can study the impact of new technologies, algorithms, and procedures on air traffic management, navigation systems, and safety protocols), training and education, system testing, and validation (e.g., test collision avoidance systems and air traffic control software), emergency preparedness (e.g., simulated scenarios can help emergency response teams prepare for critical situations, such as natural disasters or air traffic incidents), policy and regulation analysis, and traffic management optimization (different traffic management strategies can be simulated to optimize airspace utilization, reduce delays, and enhance overall efficiency). We utilized the Python library provided by *Bluesky* to interact with the network. Its data and simulation capabilities can be accessed and utilized across various programming languages and tools.

5.3. Data Preprocessing

As mentioned before, data on airblocks, sectors, opening schemes, and traffic patterns were retrieved from *The OpenSky Network*. Initially, we identified polygons created by the airblocks through their coordinates. Following this, each sector was linked to its corresponding collection of airblocks to establish the airspace volume. Throughout the day, a sector's configuration can vary, potentially merging or splitting, based on factors like traffic volume, weather conditions, ATC requirements, and more. Opening scheme data provide information about the specific configurations that each sector adopts during the day.

The simulation process encompasses a sequence of three steps.

1. For each sector, create a list of adjacent sectors.
2. Capture the precise timing of an aircraft's entry and exit into a sector based on traffic patterns of active sectors (see Algorithm 1). Challenges arise due to the segmentation of aircraft traffic. To address this, interpolation becomes crucial in merging all data points seamlessly.
3. For each aircraft, determine the sectors that it traversed along with the corresponding timestamps.

Algorithm 1

Inputs: Sectors and traffic data

Outputs: For each sector, the current list of timings when the aircraft entered and exited

Notation: WP: waypoint, FL: flight level

```
for each trajectory do:
    current_wp ← find first WP above FL180
    current_sector ← find sector for current_wp
    add entry time stamp to the list in current_sector
    while WP above FL180 do
        new_wp ← interpolate within the segment
        new_sector ← find sector for new_wp
        if new_sector ≠ current_sector then
            current_sector ← new_sector
            add entry time stamp to the list in current_sector
            add exit time stamp to the list in current_sector
end
```

5.4. Early Handover Mechanism

The early handover mechanism is illustrated in Figure 4 and described next. An ATC handoff occurs when an executive controller transfers an aircraft to the executive controller at the adjacent sector along the aircraft's route. Under nominal conditions, this *transfer of control* takes place when the aircraft crosses the boundary (blue area) between sectors, and the receiving controller assumes full control of the flight (Figure 4, left-hand side). Figure 4 (right-hand side) depicts two adjacent sectors. $Sector_i$ operates at its capacity limit, while the neighboring $Sector_k$ has low occupancy. The aircraft marked in red represents the next entry aircraft in $Sector_i$ that, if handled there, would push the sector's occupancy beyond its declared capacity. To address this situation, the early handover procedure introduces a STAM mechanism, allowing the virtual transfer of an aircraft's control from $Sector_i$ to the ATCo at the adjacent sector ($Sector_k$) under two specific preconditions:

1. The control of an aircraft can be transferred to the adjacent sector only if the aircraft trajectory is conflict-free.
2. The adjacent sector's occupancy is below its capacity, and the controllers can handle the extra workload during the early time-window duration.

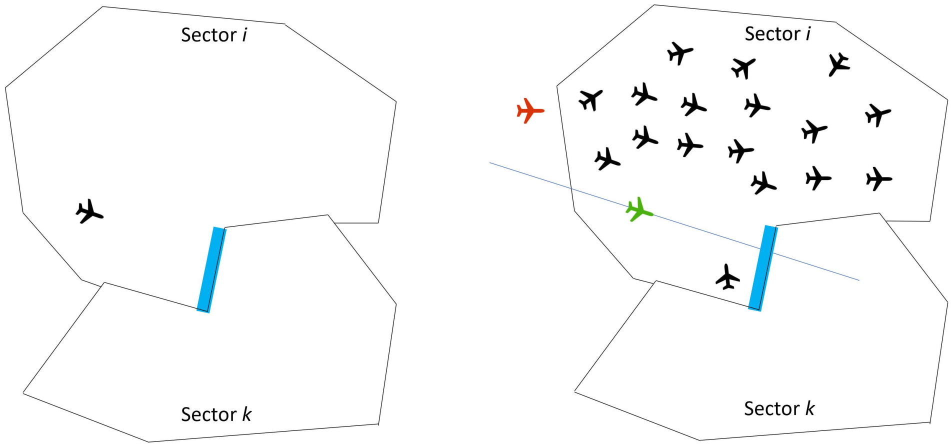


Figure 4. Representation of handover and early handover mechanisms.

Applying an early handover ensures that the STAM requirements of being local, agile, cost-effective, and effective are maintained when dealing with individual aircraft. However, this mechanism raises an open question when it comes to scaling up: how to calculate the maximum increment of traffic that adjacent sectors could handle.

5.5. Spatiotemporal Interdependencies among Adjacent Sectors

Implementing cherry-picking techniques over a small number of flights on an overloaded sector allows adjacent sectors to support DCB efficiently. This approach helps meet capacity constraints without resorting to ground regulation measures for the entire traffic flow. However, it is crucial to estimate the latent capacity of adjacent sectors to prevent potential deadlocks when flows move in opposite directions between both sectors.

Figure 5 provides a visual representation of the STAM mechanism and its sensitivity to the spatiotemporal sector interdependencies through a simple simulation exercise. The simulation tracks the evolution of occupancy indicators in two adjacent sectors, where the full flow of the aircraft entering one sector ($Sector_i$) feeds into the adjacent sector ($Sector_k$).

In Figure 5a, a peak increment in the occupancy of $Sector_i$ occurs in less than 1 h, increasing from 20 aircraft to 30 aircraft. The average dwell time (t_{dw}) in $Sector_i$ is 15 min, serving as a deterministic value for this illustration. Consequently, the observed increment in the occupancy of the adjacent $Sector_k$ follows a similar pattern to the occupancy evolution of $Sector_i$ but with a delay of 15 min. Figure 5b highlights the latent capacity in $Sector_k$, which can be utilized by the proposed early handover mechanism once $Sector_i$ reaches its maximum capacity of 30 aircraft. Figure 5c,d illustrate the same dynamics but consider a peak demand lasting for 20 min. The computation of latent capacity depends on various factors, including the dwell time of the sectors concerning adjacent sectors, traffic complexity, and demand dynamics. In Figure 5e,f, the dwell time of $Sector_i$ is increased to 20 min, resulting in a considerable increase in the latent capacity of the adjacent sector.

These visual representations demonstrate how the STAM mechanism adapts to changing demands and highlights the significance of estimating latent capacity to effectively manage air traffic flow between adjacent sectors.

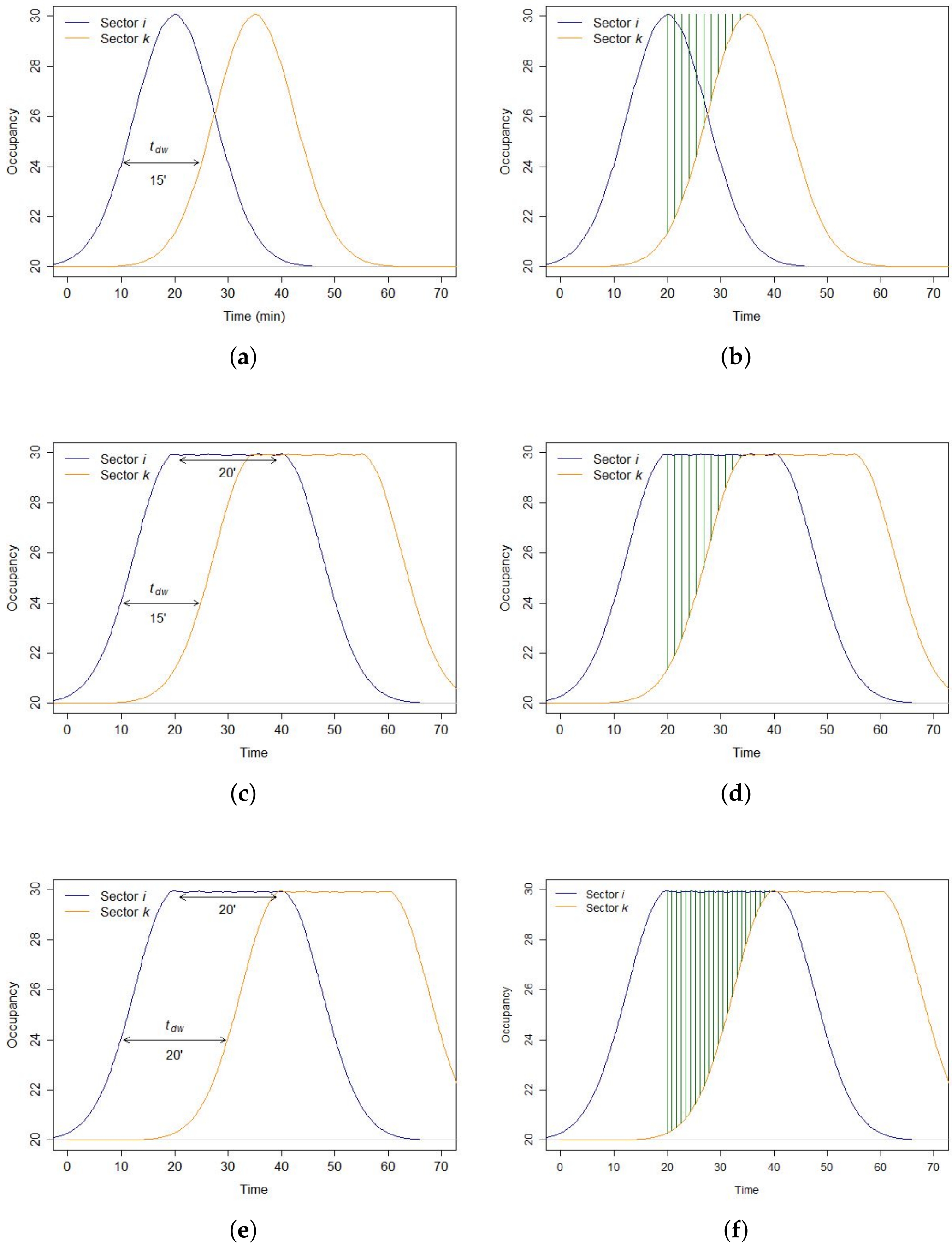


Figure 5. Dynamic occupancy in adjacent sectors considering different sector dwell times. (**a**) Average dwell time of 15 min. (**b**) Latent capacity in the case of Figure 5a. (**c**) Average dwell time of 15 minutes and peak demand lasting for 20 min. (**d**) Latent capacity in the case of Figure 5c. (**e**) Average dwell time of 20 min and peak demand lasting for 20 min. (**f**) Latent capacity in the case of Figure 5e.

6. Results

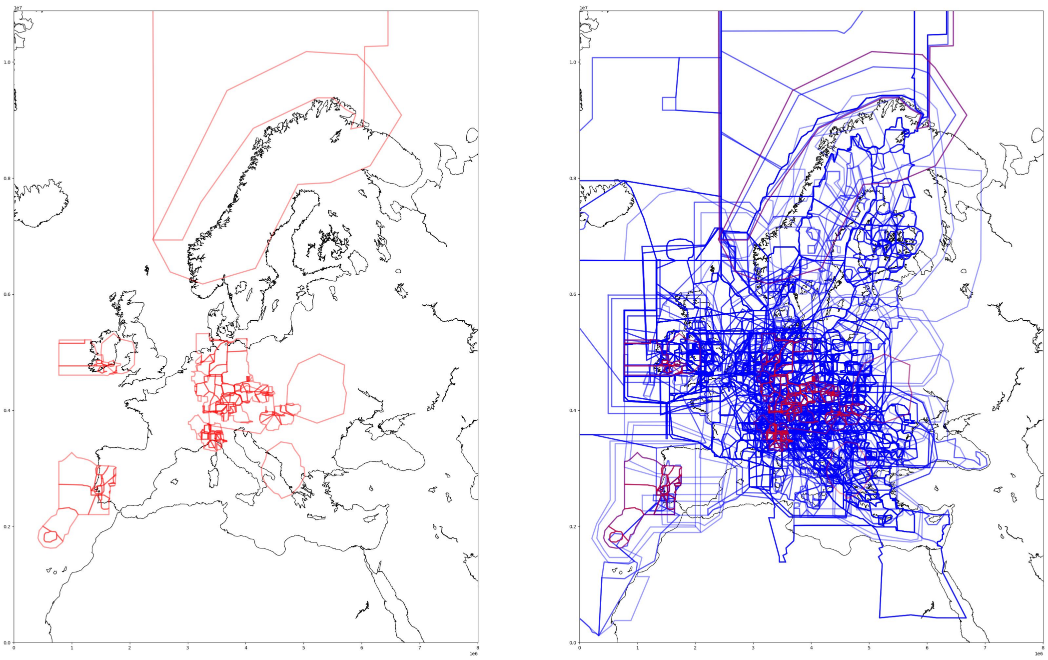
This section presents a case study that exemplifies the implementation of the proposed mechanism, alongside a thorough exploration and discussion of the advantages it offers.

6.1. Identification of the Sectors of Interest

A total of 7581 sectors are established within the European airspace; however, not all of these sectors remain active on a daily basis. Frequently, due to airspace resectorization efforts, a sector might undergo division into two or more sectors. On the chosen date of 23 September 2022, a total of 637 sectors were operational.

The primary filtering step involves excluding those sectors in which the early handover mechanism cannot be applied. A total of 411 sectors fall into this category. This quantity is notably elevated for several reasons. Firstly, these sectors are positioned on the outskirts of the designated research area, potentially intersecting with non-European zones. Secondly, these sectors exclusively supply incoming aircraft, a characteristic that is common among TMA sectors. Finally, a subset of these sectors covers an extensive geographical expanse, including some that pertain to flight information regions (FIRs). There are 226 sectors in operation that possess shared boundaries with neighboring sectors.

To better illustrate this new STAM mechanism and conduct a comprehensive study of occupancy dynamics between each sector and its neighboring counterparts, a subgroup of 14 sectors has been chosen from these 226 sectors, characterized by peak occupancies within the range of 30 to 45 aircraft. These 14 sectors encompass diverse categories, ensuring a well-rounded examination of various occupancy patterns. Among them are the elementary sector, area of interest, area of protection, elementary regulated airspace, and flight information region. Figure 6 shows the European airspace map with the boundaries of these 14 sectors of interest highlighted in red and their adjacent sectors highlighted in blue.



(**a**) (**b**)

Figure 6. European airspace map with boundaries of sectors of interest highlighted in red; (**a**) 14 sectors (with inner airblocks) of interest; (**b**) 14 sectors of interest and their adjacent sectors highlighted in blue.

6.2. Analysis of the Occupancy Correlation with the Adjacent Sectors

The selected case study focuses on a randomly chosen sector, specifically the LACCAOP sector. This sector stands out with a maximum peak of 36 aircraft, a median value of 21 aircraft, and an average of 20.28 aircraft. The sector is located in the region of the south of Italy and encompasses a part of Albania.

Figure 7 depicts the evolution of the occupancy level of the sector of interest, LACCAOP (highlighted in blue), alongside its adjacent sectors. For a better visualization, the adjacent sectors are distributed in three subfigures. Regarding the LACCAOP sector, the figure reveals a gradual traffic increase during the early morning hours, peaking at approximately 30,000 s or 8:30 a.m. Around 9:00 a.m., the sector experiences a peak, followed by a subsequent decline until roughly 10:30 a.m. Another peak emerges at 11:00 a.m., with a subsequent one observed at around 2:00 p.m. Following this, a reduction in activity takes place, interrupted by a resurgence of aircraft at around 6:00 p.m. Finally, by 8:00 p.m., the sector's aircraft count dwindles to a minimum level. In relation to the evolution of occupancy levels in the adjacent sectors, a notable diversity is apparent concerning the trends, variability, as well as minimum and maximum values. As anticipated, however, all sectors exhibit diminished values during the early and late hours of the day.

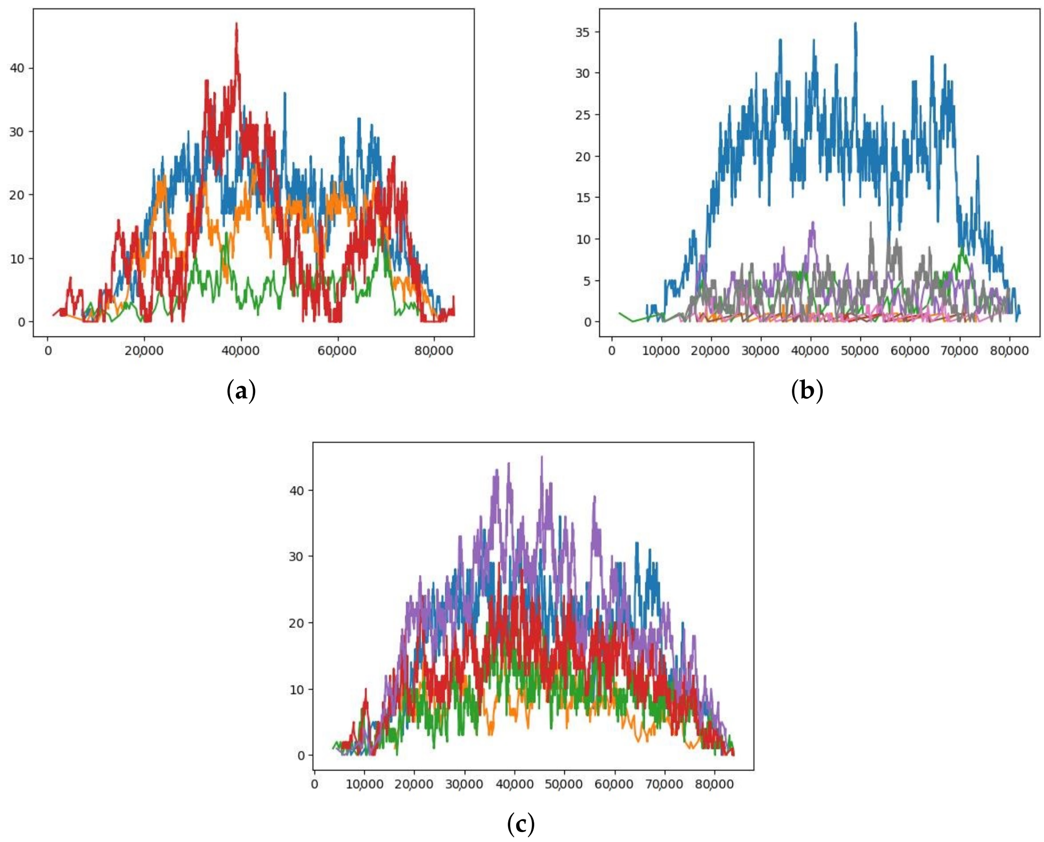


Figure 7. Evolution of the sector of interest, LACCAOP (in blue), and different adjacent sectors. (**a**) Adjacent sectors: LGGGCCAOI (orange), LGMDCCAOI (green), LBLGTEST (red). (**b**) Adjacent sectors: LGGGCCAOP (orange), LGFRA (green), LITSA420A (red), LIBBCCAOI (purple), LIRRCCAOP (pomegranate), LIBBES1 (pink), LIBBFIR (grey). (**c**) Adjacent sectors: LIRRCCAOI (orange), LYKVCCAOI (green), LYKVCCAOP (red), LQCCAOI (purple).

The Pearson correlation coefficients representing the relationship between the occupancy evolution in the sector of interest and the 25 adjacent sectors exhibit a range spanning from −0.56056 to 0.59466. The lower quartile, median quartile, and upper quartile stand at 0.07929, 0.18348, and 0.40975, respectively. Furthermore, the arithmetic mean is calculated to be 0.19817. Consequently, the correlations exhibit a relatively diminished level, indicating that, overall, there are no substantial linear associations between the evolutions. This implies that, typically, as the sector of interest encounters a rise in occupancy, culminating in its apex, a neighboring sector will seldom display a matching pattern. Consequently, the activation of the early handover mechanism could be considered to efficiently redistribute the ATC workload.

Table 1 illustrates the occupancy of the sector under study (LACCAOP) at three different peak occupancy times, together with the occupancy at the adjacent sectors.

Table 1. Occupancy count values for different peak occupancy times and sectors.

Occupancy Peak Time (s.)	LACCAOP	LGGGC CAOI	LGMD CCAOI	LBLG TEST	LGG GUIR	BLUE_ MED	LIBBC CAOP	LGGGC CAOP	LGF RA	LITSA 420A	LIBBC CAOI	LIRRC CAOP	LIBB ESS1	LIBB FIR
32,400	33	15	3	33	17	9	10	1	3	0	7	0	0	3
39,400	33	15	3	40	22	16	9	1	7	0	7	0	0	0
49,000	35	12	7	11	27	12	6	0	1	0	3	1	0	3

The correlation analysis is extended by introducing a delay factor. This consideration stems from the notion that if the sector of interest has aircraft en route to an adjacent sector, accounting for a positive delay (i.e., dwell time) can potentially increase the correlation between the occupancy levels of the sector of interest and the adjacent sector. Dwell times in this study encompass a range from 600 to 1800, with increments of 100. The delay values are selected to optimize the correlation coefficient in each case. The resultant correlation coefficients span from −0.53073 to 0.62870. Specifically, the lower quartile, median quartile, and upper quartile values are 0.07173, 0.22849, and 0.50220, respectively. Furthermore, the arithmetic mean stands at 0.24952. While these correlations exhibit higher values compared to the previous analysis, they remain relatively modest. This suggests that, overall, noteworthy linear associations between the evolutions are lacking, even with the consideration of delays.

6.3. Simulation

In order to obtain initial validation regarding the early handover mechanism, a simulation was conducted around the time when the aircraft were about to exit the sector. Figure 8 illustrates the traffic of the sector under study using the *Bluesky* simulator; it depicts the candidate aircraft that could be used for an early handover before the flow of aircraft heading toward the sector arrives at the entry point.

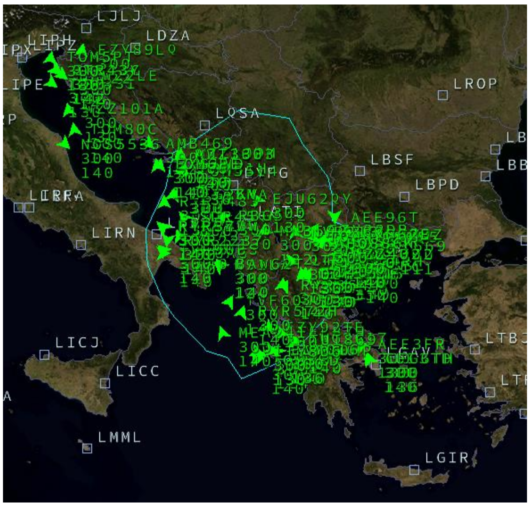


Figure 8. Traffic simulation using the *Bluesky* simulator.

At the initial stage of the simulation, the results revealed the existence of different aircraft flows due to the dwell time. Three major aircraft flows can be identified (see Figure 9). The most prominent one consists of 200 aircraft with a sector dwell time of 1800 s, which corresponds to 30 min. Additionally, two other flows can be observed, totaling 85 and 80 aircraft, where sector dwell times correspond to 25 and 33 min, respectively.

Once this initial analysis is conducted, the exploration of results continues. The hypothesis of this study revolves around the possibility of performing virtual exits, where the sector is expected to experience a peak occupancy of more than 30 aircraft.

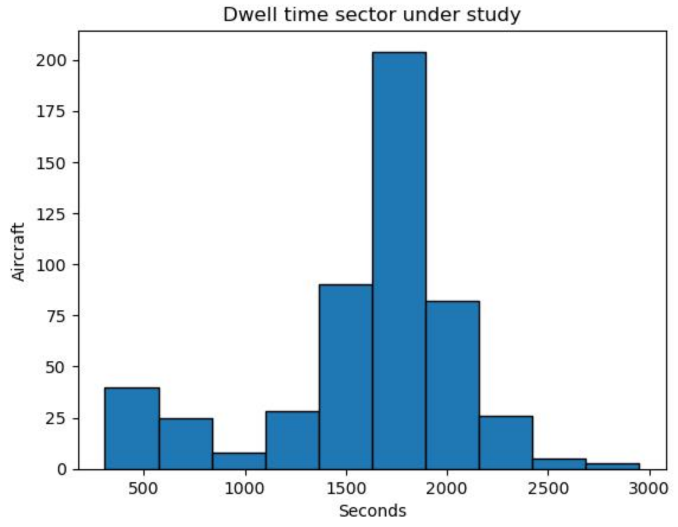
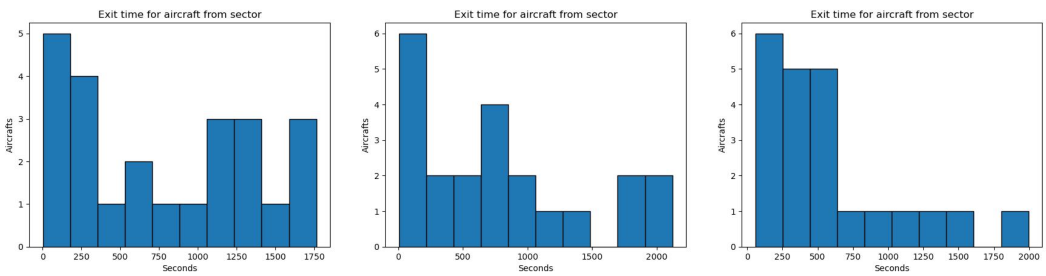


Figure 9. Histogram of the sector utilization time.

Therefore, the focus shifts to the first peak in the graph of the sector under study. Specifically, 4 min earlier than the first peak at 34,500 s (Figure 7), a virtual exit could potentially be applied to five aircraft. Figure 10a provides a histogram of the aircraft in the sector, grouped by the remaining time to leave the sector by an exit waypoint. In this paper, the authors assume that the probability of a conflict of an aircraft near the exit point is really low due to the agreement letters among sectors. As can be observed, the aircraft that are less than 8 min away from the adjacent sector provide nine candidates that could be used for an early handover, assuming that these aircraft are conflict-free.

There is a peak at 39,400 s (Figure 7) with 32 aircraft (Figure 10b). Additionally, three-and-a-half minutes before reaching this peak, one can observe that there are six aircraft for which a virtual exit could be considered, assuming that these aircraft are conflict-free. Applying this method, the sector with 25 aircraft would not experience overcapacity.

Lastly, considering another peak, such as the one occurring at 49,000 s (Figure 7), where a maximum of 36 aircraft are detected that day, it can be observed that 2 min before this peak, there are 6 aircraft for which an early handover could be considered.



(**a**) 34,260 s. (**b**) 39,190 s. (**c**) 48,880 s.

Figure 10. Histograms of exit times at different moments for aircraft from the LACCAOP sector.

Finally, the simulation provides essential information about the situation of the aircraft when they are nearing a peak of occupancy. This allows for the identification of aircraft candidates to which an early handover could be applied.

7. Discussion

Efficient ATM hinges upon the delicate balance of sector capacities, a task of paramount importance. The efficacy of this management directly affects the overall operational smoothness of air traffic systems. A significant aid in achieving this equilibrium comes from the concept of STAM, which facilitates dynamic DCB at the tactical level. This proactive approach is particularly vital in the densely packed European airspace, with thousands of sectors, where each passing day witnesses the movement of over 30,000 flights. These sectors frequently share boundaries with their neighboring counterparts, necessitating intricate coordination.

Analyzing the intricate interplay between these sectors reveals a complex picture. The Pearson correlation coefficient, a measure of how the evolution of occupancy levels is related to different sectors, often exhibits relative lowness or even negativity. This observation underscores the diversity of trends that can occur among adjacent sectors. Such diversity can arise due to variations in air traffic patterns, weather conditions, and other factors. In light of this diversity, the proposed mechanism stands to alleviate sectors with the highest occupancy levels, facilitating a smoother distribution of workloads among air traffic controllers.

The simulation process enables us to evaluate the impact of implementing the proposed STAM mechanism, avoiding ATFCM traffic regulations while keeping flows and occupancy dynamics intact. A key metric under scrutiny is the increment of traffic that the mechanism can effectively manage. Notably, the simulation sheds light on how peak traffic, which might otherwise exceed a sector's capacity, can be virtually diverted to adjacent sectors through this mechanism. This workload redistribution not only prevents congestion but also optimizes the utilization of airspace resources.

The implementation of the proposed early handover mechanism within ATM has multifaceted impacts. Economically, it can lead to enhanced operational efficiency by minimizing the amount of ATFCM traffic regulations, which in turn reduces delays and fuel consumption. This contributes to cost savings for airlines and mitigates economic losses associated with flight delays. Socially, the mechanism contributes to improved passenger experiences by minimizing travel disruptions and enhancing overall air travel reliability. Environmentally, the reduction in fuel consumption and emissions due to smoother traffic flow aligns with sustainable aviation goals, fostering a greener and more eco-friendly air travel landscape.

In the conducted simulation exercises, the prevailing policy consistently favors the selection of aircraft positioned nearer to the exit point of the sector. As the next step in advancing this approach, a prospective avenue of exploration involves the development of a sophisticated algorithm. This algorithm's core purpose will be the identification of an optimal maximum time threshold aligned with the sector boundary, an interval in which all aircraft are conflict-free. The dynamic determination of this time threshold holds the potential to revolutionize the concept of early handovers. By strategically establishing this temporal parameter, a refined pool of aircraft can be identified as prime candidates for receiving the benefits of an early handover.

8. Conclusions

In the forthcoming decades, a rise in traffic demand is predicted to occur, which will potentially strain capacity limits and increase the amount of en-route flight regulations. Despite the drawbacks for aircraft operators, traffic regulations stand are effective countermeasures used when confronting overload issues during operations, restoring stability to air traffic flow and capacity management (ATFCM). The amount of en-route flight regulations can be decreased through adaptations in the conventional sectorized air traffic control (ATC) approach, requiring innovative strategies to manage impending air traffic growth. The intricate interdependencies among air traffic management (ATM) services and the trade-offs among ATM key performance areas further complicate the pursuit of inventive solutions targeting safety, capacity, environment, and cost-efficient metrics.

In this context, this work proposes a pioneering approach centered on network capacity, involving the transfer of ATC workloads across adjacent sectors through an early handover mechanism for aircraft with different traffic patterns. This methodology offers a swift and efficient strategy to subtly adapt airspace configurations, effectively tempering peak occupancy values.

We conducted a computational experiment centered on specific sectors within the European airspace; we demonstrated the application and benefits of the proposed mechanism. We utilized real data on airblocks, sectors, opening schemes, and traffic patterns, we engaged maps, graphical tools, descriptive statistics, correlation analysis, and simulations to validate our approach through a detailed case study. The outcomes highlight the efficacy of our approach as a straightforward yet potent strategy for efficiently redistributing aircraft traffic, with the potential to reduce the necessity for en-route flight regulations.

This study suggests several avenues for future research. Firstly, expanding the computational experiments to encompass the entire European airspace during peak demand could enable the quantification of economic, environmental, and societal impacts stemming from the implementation of our approach. Secondly, the integration of machine learning techniques could facilitate the identification of scenarios where the mechanism proves most effective, with the potential for anticipatory deployment. Employing reinforcement learning may enable the formulation of policies for the mechanism's application in intricate and dynamic settings. Lastly, investigating the influence of human factors on our mechanism could lead to its refinement. Exploring workload management, human–machine interaction, and user-friendly interface designs could bolster safety and mitigate errors.

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Abbreviations

The following abbreviations are used in this manuscript:

ACC	Area Control Center
ADP	ATFCM Daily Plan
AO	Aircraft Operator
ASM	Airspace Management
ATC	Air Traffic Control
ATC TWR	ATC Tower
ATCo	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
CASA	Computer-Assisted Slot Allocation
CFMU	Central Flow Management Unit
CWP	Control Work Position
DAC	Dynamic Airspace Configuration
DAS	Dynamic Airspace Sectorization

DCB	Demand Capacity Balancing
dDCB	Dynamic DCB
ETFMS	Enhanced Tactical Flow Management System
FCA	Flight-Centric Air Traffic Control
FIR	Flight Information Region
FMP	Flow Management Positions
KPA	Key Performance Area
KPI	Key Performance Indicator
MDI	Minimum Departure Interval
MIT	Miles in Trail
NM	Network Manager
NOP	Network Operations Plan
SES	Single European Sky
SID	Standard Instrument Departure Route
STAM	Advanced Short-term ATFCM Measures
TMA	Terminal Maneuvering Area
WL	Workload

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