Enhancing capacity in Air Traffic Management

An analysis of traffic complexity and future growth projections

Master Thesis

Ioana Toanchina

Delft University of Technology

TU Delft

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by

Ioana Toanchina

Student Name	Student Number
Ioana TOANCHINA	5630800

Instructors:	Prof.dr.ir J.M. Hoekstra, Dr.ir J. Ellerbroek
Profile:	Sustainable Air Transport
Track:	Control and Operations
Faculty:	Faculty of Aerospace Engineering, Delft
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Enhancing Capacity in Air Traffic Management: An Analysis of Traffic Complexity and Future Growth Projections

Ioana Toanchină
Delft University of Technology, Delft, The Netherlands

This thesis investigates future air traffic growth projections for an en-route environment and its impact on airspace complexity. The study compares Free Route Airspace, FRA, with the traditional ATS Routes Network, assessing airspace efficiency through various complexity metrics, including flight interactions, air traffic controller workload, and traffic patterns. These complexity metrics present the dependent variables of the study. The research builds a simulation model where the independent variables are the size of airspace, the type of demand, and the operational environment. With help of BlueSky ATM Simulator, the simulation model shows how independent variables can affect the complexity metrics. Additionally to this, the study evaluates the environmental impact by measuring CO2 emissions, which are found to be significantly lower under the FRA due to more direct routing. Also, the findings of this research suggest that FRA offers more efficient traffic distribution, particularly in larger airspace areas. In smaller airspace areas, the controller workload increases due to less predictable flight paths and the more flight interactions under Free Route Airspace environment. The study concludes that FRA is advantageous for larger airspace areas, enhancing efficiency and sustainability, but it also introduces challenges in managing air traffic, particularly in smaller or highly concentrated airspace environments.

Nomenclature

AD	=	Adjusted Density
ANSP	=	Air Navigation Service Provider
ATC	=	Air Traffic Control
ATCO	=	Air Traffic Control Officer
ATM	=	Air Traffic Management
ATS	=	Air Traffic Services
COCA	=	Complexity and Capacity Analysis
eAIP	=	Electronic Aeronautical Information Publication
ECAC Area	=	European Civil Aviation Conference Area
FAA	=	Federal Aviation Administration
FBZ	=	Forbidden Beam Zone
FRA	=	Free Route Airspace
HDIF	=	Horizontal Different Interacting Flows
IFR	=	Instrument Flight Rules
MUAC	=	Maastricht Upper Area Control Centre
NEST	=	Network Strategic Tool Software
PRU	=	Performance Review Unit
R&D	=	Research and Development
RAMS	=	Reorganized ATC Mathematical Simulator
SAF	=	Sustainable Aviation Fuel
SDIF	=	Speed Different Interacting Flows
SES	=	Single European Sky
SSD	=	Solution-Space Diagram
VDIF	=	Vertical Different Interacting Flows

I. Introduction

Aviation industry is considered as a dynamic system. It is highly sensitive to various factors such as economic fluctuations, natural disasters, pandemics, and costumer behavior.[1] Due to these factors, the aviation industry is one of the most volatile sectors in transportation, often experiencing significant changes in profitability and stability. Over the years, air transportation has made significant advancements in technology and performance to respond properly to these external factors. For example, a statistical report from EUROCONTROL shows that around one million flights were registered in the European Civil Aviation Conference, ECAC, zone in July 2019. However, the COVID-19 pandemic fundamentally altered this historical record. In April 2020, less than a year later, only about 109,000 flights were registered in the ECAC zone. [2]. This dramatic decrease of almost 90% of traffic can be explained by the industry's volatility and its sensitivity to external factors.

To assist aviation stakeholders in recovering, several forecast and predictions services have implemented different recovery scenarios. In addition to this, most of the reports estimate a surpassing of 2019 records in the near future. In reality, today's air traffic is growing faster than expected. It has nearly fully recovered in less than five years after the pandemic.[3] Thus, this unexpected and fast growth of traffic presents both opportunities and challenges for the industry. For instance, one of the biggest opportunities is economic expansion. As the number of flights increases, so does the profit. In contrast, one of the biggest challenges is the accommodation of this traffic without altering the adjacent parts of the system, such as human performance, safety and even the environment. For example, the more flights in the sky, the more congested airspace. This leads to the bigger number of delays.

Therefore, to combat this significant growth of air traffic, a multi-faceted approach is needed. For example, airlines and aircraft manufacturers are investing in advancing Sustainable Aviation Fuels, SAFs. At the same time, airports are adopting green practices, such as using renewable energy and electric ground support equipment. Effective capacity management is another key strategy for accommodating the rise of traffic. However, despite the development of a better capacity management tools to prevent congestion and delays, a major challenge remains: the physical limitations of the airspace. Unfortunately, this constraint cannot be modified from ground. The Air Traffic Management, ATM, division must focus on adapting the current airspace capabilities to meet customers' needs.

As a collaborative effort, by various European air navigation service providers, ANSPs, Eurocontrol, and other stakeholders within the aviation industry, the concept of Free Route Airspace, FRA, appeared in 2004 as part of Single European Sky, SES, Program. The idea of FRA emerged from the need to increase efficiency and flexibility in European airspace. It represents an alternative to Air Traffic Services, ATS, Routes Network. Basically, FRA allows airlines to plan their flight paths more flexible and freely without following a certain air route.[4] This concept does not increase the physical size of the airspace, but it creates the possibility to obtain more air paths within the same airspace area. This can act as solution in accommodating huge demand of traffic. Moreover, the ultimate goal of implementing the FRA is to achieve a more integrated and seamless airspace that can function as a single airspace across the continent.

Therefore, the main objective of this research paper is to analyse how to accommodate increased demand of traffic in an optimal way from the capacity management point of view. This thesis takes into account the physical limitation of the airspace capacity. It includes analysis of different scenarios on how future growth projections can be handled without increasing environmental impact, affecting the human performance, or altering the safety in aviation. However, in reality, airspace capacity does not refer just to the number of aircraft flying in a specific area, but rather to the overall system. To achieve the objective of the paper, a complexity assessment with the focus of the difference between FRA and ATS Routes Network is developed. This assessment evaluates high demands from different perspectives, including human performance, airspace structure, and conflict detection. Moreover, the sustainability of this approach cannot be ignored. As traffic potentially increases, aviation industry needs to adhere to the environmental regulations. While FRA can reduce individual flight emissions by enabling more direct routes, the overall increase in demand could offset some of these environmental gains by raising total emissions. In this matter, this thesis also covers the evaluation of total CO_2 emissions.

Thus, this research paper is structured as follows. The section II describes the context of the research. A review of the literature on airspace capacity, highlighting various methodologies and metrics used to assess complexity and capacity in ATM is shown in section III. Further, section IV outlines the methodology of this study, including the major steps of the research. The experiment set-up and the description of the variables are explained in section V. The outcome of the traffic scenarios and the post-analysis of the results are presented in section VI. This is followed by a discussion of the findings. Lastly, the research paper contains the conclusions of the study in section VIII. It also highlights the limitations and recommendation for future work.

II. Problem Statement

The aviation sector is currently facing a significant challenge due to the unprecedented growth rate in air traffic. The EUROCONTROL Forecast program estimates a 7% increase in traffic during the summer of 2024.[5] Typically, growth rates in the aviation industry are below 5%. Therefore, this projected 7% increase poses a significant challenge. Moreover, as it can be seen in Appendix on Figure 25, most of the countries surpass this 5% growth comparing to the previous year. This increase makes the entire airspace more prone to congestion and delays. Furthermore, due to the existing geopolitical situation, the amount of military actions has increased. Today, military activities occupy 20% of Europe's airspace. As a result, the airspace has become a complicated system that can be controlled only cooperatively.[6] To promote cooperation, EUROCONTROL has launched the Summer 2024 Preparation project. This initiative aims to involve all sectors of the industry into collaboration and joint contribution. The goal of this initiative is to ensure efficient and optimal operations during the anticipated rise in air traffic. One of the main goals of this strategy is to increase airspace capacity by creating a seamless airspace organization.[7] This includes disciplined flight plan execution, prioritizing first rotations for on-time departures, delivering agreed capacities, and maintaining realistic schedules, including turnaround times.

Beyond these improvements, the introduction of FRA provides a promising solution for more efficient airspace use. The implementation of FRA allows more efficient airspace usage by enabling airlines to plan their routes freely without adhering to fixed ones. Although FRA does not expand the physical size of the airspace, it creates more air paths within the same area. At a first sight, this concept seems well-suited for managing high traffic demands effectively. However, the transition to a fully integrated airspace under FRA by 2025 where national boundaries are less important, raises several significant questions. How can airspace capacity be optimized under FRA implementation for future traffic growth scenarios? How does FRA implementation keep balance between accommodating high demands of traffic and maintaining low level of environmental impact? How effective is the implementation of FRA across Europe from human performance perspective?

All these questions reinforce the objective of the thesis, which is **to examine how the implementation of FRA impacts airspace capacity in the context of future traffic growths.** To achieve the research objective outlined above, the paper will examine the subject from multiple perspectives. For instance, airspace management is considered a subsystem within the ATM system. This subsystem is inherently complex and influenced by many external factors. Airspace capacity, for example, is not solely determined by the number of aircraft counted at a given time. It is influenced by the performance of air traffic controllers, the conflict rate, and the balance between air traffic demand and sustainability. Therefore, when airspace capacity is evaluated, the entire complexity of the airspace is taken into consideration. Based on this criteria, the first research question addresses the complexity assessment in the relation to the implementation of FRA.

In addition to these challenges implied by future growth projections, the European Commission has set an ambitious target of achieving net-zero greenhouse gas emissions by 2050 as part of its European Green Deal. This goal is major to the EU's efforts to combat climate change. Despite its relatively small share of overall emissions, the aviation sector's impact becomes significant as air travel demand increases. To address this concern, the second research question examines the total emissions resulting from FRA implementation. Thus, the research questions addressed in this paper are:

1) How does the implementation of FRA impact sector capacity when assessed using different traffic complexity metrics?
2) How does the implementation of FRA contribute to the sustainability of air transport?

III. Previous Work

Airspace capacity has been extensively researched in the literature, with a focus on important of its role in managing air traffic efficiently. Capacity is often initially defined as the total number of aircraft within an airspace during a given period. However, this definition is only partially correct, as airspace capacity can vary over time and is influenced by more than just the number of aircraft. Several studies show this aspect. For example, studies such as [8] and [9] link the airspace capacity with the air traffic controllers workload. These studies conclude that optimal air traffic controller performance is not solely dependent on handling the maximum number of aircraft in the airspace. Moreover, other studies, including [10], [11], and [12], estimate airspace capacity with respect to airspace configuration, safety operational environment, and meteorological factors. Therefore, to accurately assess airspace capacity, several complexity metrics must be considered. These metrics include flight interactions, air traffic controller workload, and operational environment. Each complexity metric is further defined by various indicators, such as conflict rates, dynamic changes in altitude, speed, or heading, and other relevant factors that contribute to the overall complexity of air traffic management.

A. Flight Interactions

Flight interactions refer to the several ways the air traffic interact within the airspace, including changes in altitude, direction, and speed. These interactions significantly influence the complexity of managing air traffic. Figure 1 gives a small example of how these flight interactions may impact the complexity of the airspace. The example involves two aircraft which are displayed with green rectangular shapes. Attached to these shapes, the green lines represent where the aircraft will be in the next two minutes.

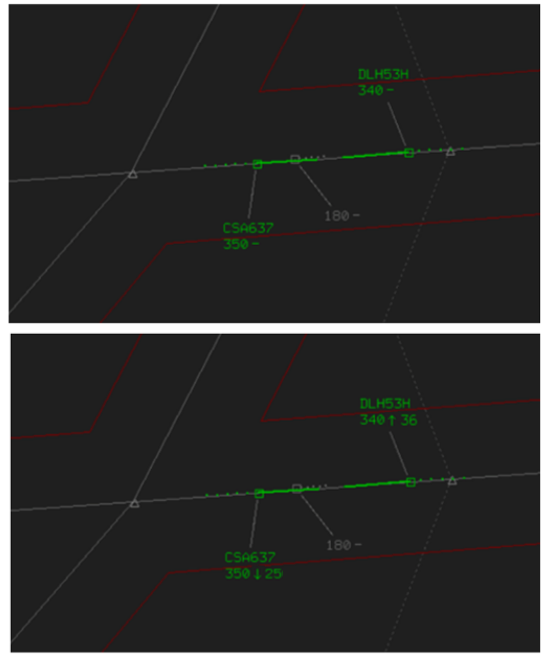


Figure 1. Scenarios of flight interactions. Generated by EUROCONTROL simulator software

Let's consider the first scenario from left-hand side. In this scenario, both aircraft are following constant altitudes. The difference in altitudes between them is 1000 ft, which according to the minimum separation standards, it represents a safety measure for the vertical profile. Therefore, without any change in altitude they are not at risk of conflict. In contrast, let's consider the second scenario displayed on the right-hand side. In this scenario, the two aircraft are in the process of changing their flight levels. Although the current vertical separation is safe, the fact that they are ascending or descending towards each other introduces the potential for conflict.

The complexity of traffic is higher in the second scenario than the first one and this is caused by the need of maintaining the safe separation between aircraft. But what happens when instead of two aircraft there are multiple aircraft which are changing their flight levels? How does the complexity changes in this scenario? What happens if in addition to changes in altitude, changes in heading and speed occur?

To answer these questions, some studies assess the complexity through the dynamic density model. In 1990, the Federal Aviation Administration, FAA, introduced this model to quantify the complexity of air traffic within a sector.[13] The model considers eight variables. Apart from number of aircraft, the model includes the changes in altitude, heading and speed. It also introduces the weather, distance between aircraft, and intersecting flight paths. All these variables may increase the difficulty of maintaining safe separation between aircraft.

Later on, this model has got adapted to suit different assessments of complexity. For example, in a study conducted by MUAC, two adaptations of the original model are presented, one of which includes 16 variables.[14] This study compares these models to better understand how different factors contribute to overall airspace complexity. Moreover, the study finds that both dynamic density models provide valuable insights into air traffic complexity. However, the model with 16 variables offers a more detailed analysis allowing for a more accurate assessment of potential airspace congestion. Published in 2002, [15] explores methods for measuring and predicting the complexity of air traffic sector using a model of dynamic density with nine variables. The study demonstrates that by incorporating variables such as the number of aircraft, their proximity, and various changes in speed, altitude, and heading, the dynamic density model provides a better assessment of air traffic complexity. With only seven variables [16] founds that dynamic density metrics can effectively predict sector complexity and help in real-time traffic flow management.

Therefore, dynamic density is an aggregate metric which combines the static and dynamic characteristics. In other words, this metric is able to include the dynamic behavior of aircraft within the sector. In general, dynamic density is a weighted model where the formula typically follows Equation 1.

$$DD = \sum_{i=1}^{n} F_i W_i \tag{1}$$

The formula represents the summation of complexity indicators, noted with F_i, multiplied by its weight component, W_i. This component usually is computed using regression models. Consequently, the drawback of this approach is that it can only be applied to scenarios that are fairly similar to the baseline scenario, because the weights need to be recomputed and re-validated for each case. n is the number of factors considered in the model.

While the weighted model offers a precise evaluation of a specific airspace environment, the unweighted model for dynamic density exists. This approach treats all factors equally, simplifying the analysis. It avoids the complexity of determining appropriate weights and it is more straightforward to different scenarios without the need for recalibration. For example, the Complexity and Capacity Analysis, COCA, Project by EUROCONTROL develops an unweighted dynamic density model.[17] The project shows that even without weighting, the model could provide valuable insights into air traffic management. As example, in the article, a complexity assessment is conducted based on a change in Brussels Sector Group. The article analyses the impact of this sector change, revealing that after the adjustment, the complexity score decreased. This reduction indicated that the sector reconfiguration around the REMBA navaid successfully lowered the air traffic controller workload and improved overall air traffic management efficiency in that area.

B. Air Traffic Controller Workload

The main finding of the article [18] is that there is a strong correlation between air traffic demand, safety and complexity in high-density airspace areas. By analysing the relationship between these factors, the article highlights the importance of managing these factors to ensure that air traffic controllers can maintain safe operations, even in high demand scenarios. In addition to this, [19] explores the direct connection between safety and air traffic controllers workload. The article shows how excessive workload can lead to safety risks. Therefore, air traffic controllers workload plays an important role in estimating the capacity of the airspace area.

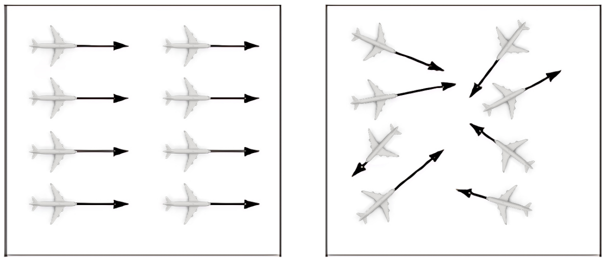


Figure 2. Different air traffic situations with the same density

To illustrate how the air traffic controllers workload can affect the airspace capacity, let's consider the two scenarios from Figure 2. On the left-hand side, aircraft are shown flying parallel trajectories. The arrows show the direction and the speed of the aircraft. Therefore, it can be noted that the aircraft are flying in the same direction with same speed because in this example the arrows have same orientation and size. If the safe separation is maintained among aircraft, the airspace can easily be managed and controlled. However, in reality, the aircraft are flying on different directions and different speeds and even different flight levels. A better overview of real world is shown in right-hand side of the picture. This scenario leads to a more complex and chaotic traffic pattern which increases the attention of the air traffic controllers. This means that the air traffic controllers must coordinate to avoid potential conflicts, manage different flight paths, and ensure safe separation between aircraft. Consequently, the capacity of the airspace can even be reduced because the increased cognitive demand on the controllers.

Therefore, air traffic controllers are the primary operators in managing the air traffic and estimating the airspace capacity. Because of that, human factor is central to several studies in the literature. For example, the study [20] assesses the complexity over the airspace with respect to the workload of the air traffic controller. By using a Reorganized ATC Mathematical Simulator, RAMS, controller workload model, the study finds that high workload levels correlate with reduced capacity as controllers reach their cognitive limits, making it challenging to manage additional traffic safely. Additionally, more complex airspace sectors with multiple crossing flight paths or varying altitudes require more intensive monitoring and coordination. [21] explores the free routing concept impact on the workload of controllers. The findings of this article suggest that while direct flight paths improve the airspace usage, it also creates the complexity of air traffic management. This complexity arises from the need to manage more varied and less predictable flight trajectories, which can elevate the workload for controllers.

Another example is the study from EUROCONTROL. [22] explores the factors contributing to cognitive complexity in air traffic control and their impact on controller workload and safety. One of the findings of this research project points out that complexity is influenced by traffic density, sector design, and dynamic changes in traffic. Also, [23] examines how increased air traffic volumes impact air traffic controller workload and performance. The study shows that as air traffic volume increases, the workload on controllers also rises significantly. This phenomena leads to potential risk of errors with a decrease in performance. Obviously, the size of airspace affects the airspace capacity. However, the size of an airspace area may affect the human performance as well. Therefore, [24] explores how different sector sizes and traffic densities affect the workload of the air traffic controllers. Based on a simulation-based approach, the article shows that larger sector sizes, combined with high traffic density, significantly increase controller workload and reduce performance.

There are studies which use the visualisation method of Solution-Space Diagram, SSD, in order to estimate the impact of complexity on air traffic controller. According to [25], this method is more reliable sector complexity metric than the dynamic density. Basically, the SSD is used to visualize the available maneuvering options for aircraft, helping to quantify controller workload. A drawback of this method is that it represents a 2D visualisation, where differences in altitudes are not considered. [25] mentions that the approach is accurate if the flights are stable in vertical movements. On the other hand, [26] implements this approach adding the third dimension as well. The study finds that SSDs offer a detailed and reliable assessment of air traffic complexity, better capturing the nuances of controller workload compared to traditional metrics. However, the visualisation approach is not enough to determine the complexity within an airspace area. To estimate a workload index that provides more insight into complexity, Equation 2 is utilized.

$$\text{Workload Index} = \frac{1}{n}\sum_{i=1}^{n}\frac{\text{Unsafe Area}_i}{\text{Total Area of Options}_i} \quad (2)$$

For each aircraft i out of the total n aircraft within the airspace, the calculation is made to determine how much of the *Total Area of Options* is occupied by the *Unsafe Area*. Unsafe area is defined as the area where the controlled aircraft is not allowed to fly; this represents the options where the aircraft risks to have a conflict with another traffic. The result is expressed as a percentage.

C. Operational Environment

In [21] it is estimated the workload of air traffic controller and how the complexity of the airspace changes when are used direct routes. As it was mentioned before, the study reveals that the choice of environment influences controller workload, airspace efficiency, and safety. Moreover, [10] finds that airspace capacity is well linked to the airspace configuration and its physical limitations. Using Artificial Intelligence, AI, models, the study shows that the capacity of the traffic handled by ATC can be determined by the sector configuration.

Another study, which evaluates the Croatian airspace, [27] mentions that the introduction of free routes reduces overall air traffic complexity. Through the Network Strategic Tool software, NEST, it is shown that FRA has a mitigating effect on complexity despite higher traffic volumes. While free routing may reduce the flight time, fuel consumption, and distance flown of the flights, [28] estimates how FRA also increases the traffic complexity complexity and conflicts due to the more dynamic routing. The same findings are presented in [29]. The study concludes that separation losses could occur more frequently in FRA due to the lack of fixed routes. On the other hand, [30] examines various complexity metrics in the context of ATS Routes Network. The study suggests that traditional route networks, while providing structured and predictable paths, can lead to increased complexity in high-density areas.

A comparison between free routing and fixed fly paths is assessed in [31]. The article shows that the fractal dimension increases with the transition to the free flight operations. The method used in the article is fractal dimension approach. This method is used because it provides a quantitative measure of how an object or pattern fills space at different scales. In ATM, fractal dimension can capture the irregular patterns of the traffic flows reflecting the complexity of the airspace structure. For example, let's consider a busy airspace sector where aircraft are flying on fixed routes. This pattern may appear complex, but in reality the flights paths are regular and predictable, leading to a relatively low value of fractal dimension. In contrast, in Free Route Airspace, the distribution of routes could be more irregular and varied. The fractal dimension would likely be higher in this case, indicating greater complexity due to the less predictable and more varied use of space.

IV. Methodology

As observed in the literature, the factors contributing to determining airspace capacity are interconnected, influencing each other. For example, different flight interactions may affect the workload of air traffic controller. The workload of air traffic controller may alter the safety of the flights. Also, the operational environment may affect the flight patterns and traffic flows. Therefore, to address this interconnections, the methodology of this thesis incorporates multiple complexity metrics that consider various factors. Also, to understand the impact of FRA on complexity, the assessment of complexity metrics is build on the ATS Routes scenarios as well. In this matter, it allows for a more comprehensive understanding of air traffic complexity and how to accommodate higher traffic volumes.

Thus, in order to achieve the research objective, the methodology applied on this study consists of five major steps. An overview of the steps used in this study are shown in Figure 3. The first step represents the data pre-processing, highlighted with dark grey. Then the data preparation phase is displayed with light grey. With these two steps, the data is prepared for the simulation model. Further, represented by the green color is the complexity model phase. This is integrated in the simulation model, which is represented by the purple color. The complexity model phase includes building the complexity metrics. The last step, illustrated in blue, is the post-analysis phase, in which the complexity assessment is made.

A. Assumptions

Before delving into the explanation of the steps, due to the limitations of the research project, few assumptions are considered.

- **Only en-route air traffic is considered:** Only the flights that are on en-route environment between FL240 and FL470 are considered.
- **The flight data information is only provided for Instrument Flight Rules, IFR, flights:** The data does not include VFR or military traffic.
- **No weather data is taking into consideration:** Due to the lack of historical weather information data, the model is created with 0 weather impact. The wind direction and wind speed are set to 0.
- **There are three phases of flight considered in en-route environment:** If the rate of climb/descent is equal or bigger than 500 ft per minute, then the aircraft is in a climb/descent phase. If this rate is smaller than 500 ft per minute, then the aircraft is in cruise phase.
- **A free route is considered from entry to exit point of the airspace:** There are no intermediate points on a free route.
- **Intermediate points are considered entry or exit points:** Based on the above assumption, all intermediate points are considered entry-exit points.
- **Unrecognized aircraft type are changed with recognized ones:** Due to the limitation of the database of aircraft types, there are a few types which are not included in the dataset. Therefore, all the unrecognized aircraft types are changed to the closest type of the original one which can be found in the database. The changes of the aircraft type are shown in Table 22.

B. Data Collection Phase

1. Data Sources

The data used in the model can be divided in two categories, traffic data and airspace data. Since two operational environments are used in the model, airspace data is subdivided in FRA data and ATS routes data. FRA data contains the points of FRA and ATS routes data contains the routes of the ATS Routes Network. While traffic data is pre-processed before being integrated in the model, the airspace data is directly computed based on the area of interest.

1.1 Traffic Data

The traffic data is imported from the EUROCONTROL R&D database. It contains flight information regarding the commercial flights over a 24 hours time frame across ECAC. The model includes the data from a weekday, 6th June 2018. The choice of the date has been made by selecting the most recent data available. Since peak traffic is recorded across Europe during the summer, month June is selected. Moreover, the reason of choosing weekday data is that weekdays typically represent more consistent and higher traffic volumes. Two types of flights are exported: the flight paths submitted by airlines to the EUROCONTROL Network Manager and radar observations of the actual flight paths. A comprehensive explanation of the traffic data can be found in Appendix subsection A.D in Table 21.

1.2 Airspace Data

Airspace data contains the geographic boundaries of the airspace areas used in the model. In this research paper, three areas are evaluated. The smallest airspace is delimited by the real boundaries of the Hannover Sector Group, HAN. This sector group is part of the Maastricht Upper Area Control Centre, MUAC, airspace. It is located mainly above Germany. The medium airspace considered is MUAC airspace. The choice for MUAC is based on the complexity level that the sector entails. For the largest area used in the model, a fictive airspace area is computed. This airspace area represents a part of Central, South and East of Europe. In the model, this airspace area is named CSE. The choice was made based on the availability of data. The data used in computing each of the airspace areas is explained in Appendix in

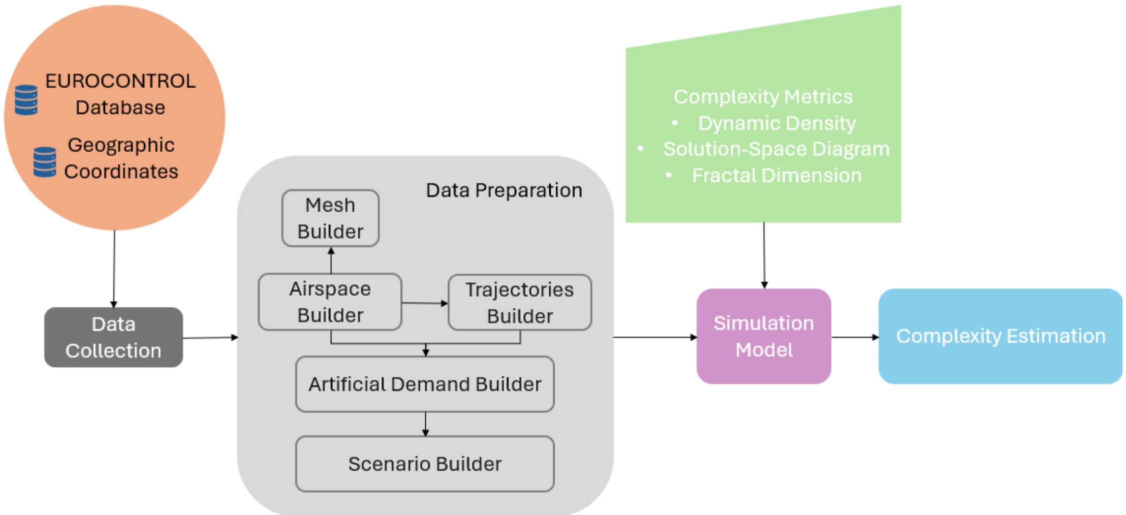


Figure 3. Methodology overview flowchart

Table 20.

In the model, airspace data acts as a filter by determining which traffic data is relevant based on the selected airspace. The traffic data that passes through this filter is then included in the scenario. Thus, the simulation focuses only on the flights passing through the specific airspace.

1.3 Airspace Structure Data

To create the operational environment, the structure of the airspace is computed. For FRA, the updated database of 2023 from EUROCONTROL is used. This database contains all FRA points within ECAC. Each point is labeled as entry, exit or intermediate point. The difference between labels is as follows; when an aircraft is entering the airspace, it can enter via entry or intermediate points. However, when the aircraft is exiting the airspace, it chooses only exit or intermediate points. Moreover, through the airspace, the aircraft can fly over an intermediate point. The dataset used for ATS Routes Network is exported from the Electronic Aeronautical Information Publications, eAIPs. However, due to the lack of data from the eAIPs, this dataset is only used to verify the ATS trajectories of the traffic.

2. Data Cleaning Process

Initially, data exported from EUROCONTROL database represents raw data. Therefore, a cleaning process is applied. The cleaning process consists of time and date adjustments. Since the dataset covers all the flights of ECAC area, in cleaning process all the flights which are not transiting CSE airspace are removed.

C. Data Preparation Phase

Once the data is cleaned, it is further processed. The data preparation phase consists of multiple modules. For example, the scenario builder module is specially intended for BlueSKy software due to the format in which it is created.

1. Environment Definition

The first module is the environment definition. As mentioned before, during the simulations, only the flights across specific airspace areas are considered. Basically, this module is dedicated to create the airspace, defines the operational environment and adjust the flights. When defining the airspace environment, two major areas are computed; the Experiment Area, which represents the real polygon-shaped airspace, and the Traffic Area, which is a rectangular shaped area around the Experiment Area. This can be seen in Figure 26 in Appendix subsection A.B. All the aircraft which are in the Traffic Area and not in the Experiment Area are called neighborhood traffic. In reality, this type of traffic plays an important role in managing the air traffic due to the strategies applied of air traffic controllers.

2. Mesh Builder

This module is necessary because some of the complexity metrics use meshing approach. The usage of a mesh facilitates the understanding of the metric across the entire airspace. Moreover, it gives a better overview of the traffic flow displacement, highlighting the hotspots within the airspace. Integrating the freedom of choosing the flight paths inside the airspace area, an invisible hotspot may occur, so the creation of a mesh is essential. Therefore, once the environment is defined, the mesh dedicated for the specific airspace is computed.

In short, this approach involves dividing the area into identical 4D cells, three spatial parameters and one temporal parameter. Figure 4 shows the spatial parameters of the cell used in this study. While the temporal parameter remains unchanged during all the simulations, the spatial components vary. The variants of these parameters are based on the airspace area.

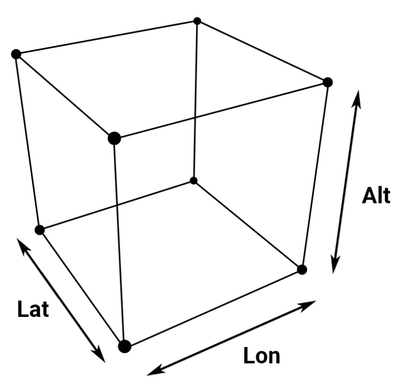


Figure 4. Cell Dimension of the mesh

Since the airspace is not a regular shape, some of the cell may contain more uncontrolled airspace than the controlled one. To prevent this, an activation sign is assigned to each cell. Basically, an active cell means that the measurements will take place in that cell during the simulation. Moreover, a cell is considered to be active if and only if its center is included in the airspace's boundaries. Also, to prevent the boundary effects, a spatial displacement of the mesh is applied. Based on the complexity metric that is computed, the number of displacements vary. Furthermore, the mesh can be shifted in all three dimensions, namely latitude, longitude, and altitude. For each direction, the shift is considered to be half of the cell's length. A detailed explanation of how the mesh is computed is described in Appendix subsection A.C.

3. Trajectories Builder

To achieve the objectives of this thesis, three distinct types of flights are developed. The first one represents the actual traffic, the second follows the ATS Routes Network, and the third utilizes Free Route Airspace. One of the dataset provides actual trajectories. Based on this dataset, FRA and ATS trajectories are computed. Therefore, since FRA and ATS Routes flights are computed artificially, the actual scenario is used as reference.

In 2018, there were no declared full-FRA areas within the region of interest. Moreover, the route data exported from eAIPs is incomplete due to the information availability. Therefore, the ATS trajectories are constructed using filled-in trajectory paths. The filled-in flight paths represent the flight planning introduced before the actual flight. The main difference between actual and filled-in trajectories is the air traffic controllers input. In reality they may provide clearances and direct commands to the pilots, allowing them to shorten their flight. However, with the available information regarding routes, a temporary route network is created to validate the filled-in trajectories. For the FRA flights computation, the process is as follows. Once an aircraft enters the Traffic Area, its actual route is changed and it flies directly to the closest entry or intermediate point of its original entering point within the Experiment Area. The same rule is applied when the aircraft is approaching the exit of the airspace. It searches the closest exit or intermediate point to the original exit point of the actual trajectory within Experiment Area. Based on these new points, new distance flown, time, flight path, and flight level are updated accordingly.

For instance, let's take as example the scenario presented in Figure 5. The flight is approaching the Traffic Area, marked with green, from north-west. The flight is flying across the Experiment Area to Italy. So, it is exiting the airspace through the south-east part. The actual flight path of the flight is represented by black. Based on this actual trajectory, the other two cases are created. In red, it can be seen the free route. This route represents the closest direct route found from the actual one. In addition to that, the blue route is the route followed by fixed routes. The FRA points are shown as green circles and the ATS routes as dark grey dashed lines on the map.

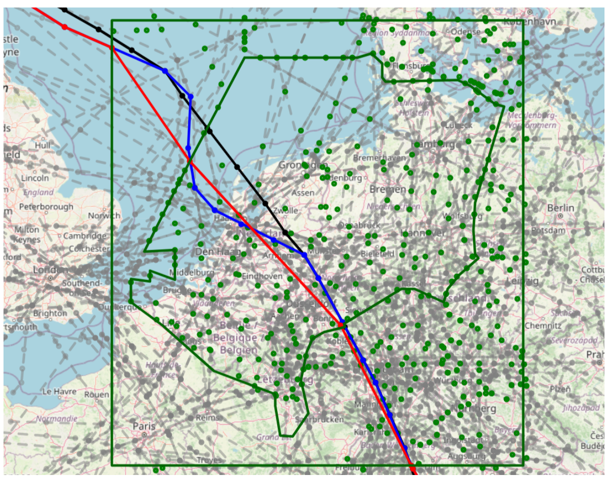


Figure 5. Computed Trajectories for One Aircraft in MUAC (Actual Trajectory - Black, ATS Routes Trajectory - Blue, Free Roue Trajectory - Red

4. Artificial Demand Creation

The actual demand of the traffic from 2018 was high. However, the volume of traffic was high for that period and it is expected to be higher in the near future. Therefore, in this study this demand is considered normal demand and artificially two other demands are created. To achieve this, a time-shifting methodology was applied. Based on the methodology outlined in [32], the time compression method is integrated into the model. This method requires a time compression factor between 0 and 1. This factor helps to separate the artificial individual demand from the original one. This separation is essential because of safety conditions. Essentially, the artificially generated traffic should be distinct from the original traffic. It also needs to ensure a sufficient gap before both aircraft departures. For this study, the minimum standard separation criteria requires a horizontal separation of 5 NM or a vertical separation of 1000 ft. Therefore, considering the safety aspects, the two artificial demands are computed. One represents high level of demand and the other one is considered as super high demand.

5. Scenario Builder

Once the flights are defined and the artificial demand is created, the scenarios are computed. The building of the scenarios is consistent with the standard of BlueSky. The file exported is *.scn* and it contains the correct script for the software. A short example of how a scenario file in BlueSky is computed is shown in Figure 31 in subsection A.E.

D. Simulation Model

In the simulation model, the computed trajectories are integrated and evaluated through a complexity model. The complexity model is computed by three complexity metrics, each one dedicated for a specific category. The first one is representative for the flight interactions of the airspace areas, one is dedicated for estimating the workload of the controller, and the last one is looking into the evaluation of the structure of the airspace. The choice for these three complexity metrics is as follows. The complexity metric dedicated for flight interactions help evaluate potential conflicts and the complexity of managing multiple aircraft simultaneously. The metric of workload assesses the cognitive demands on air traffic controllers, ensuring that their capacity is not exceeded. The complexity metric dedicated for the operational environment helps in understanding how the design of airspace affects traffic flow and controller workload. Together, these metrics provide a comprehensive picture of how well the system can handle high traffic volumes.

1. Unweighted Dynamic Density Metric

In order to capture the flight interactions among aircraft within the airspace, an unweighted dynamic density model is computed. The model is based on the theory from [33]. It captures the dynamic density over the airspace in a given period of time. There are four dimensions of complexity which are taking into account during the simulations. Each dimension is described by a complexity indicator. The variables included in this model are shown in Table 1.

Table 1. Complexity Variables Integrated in Unweighted Dynamic Density Model

Complexity Dimension	**Complexity Indicator**
Traffic Evolution	Potential Vertical Interactions
Flow Structure	Potential Horizontal Interactions
Traffic Mix	Potential Speed Interactions
Traffic Density	Adjusted Density

The description of each dimension and the dedicated complexity indicator are also presented in Appendix subsection A.G in Table 23. Traffic evolution assesses the complexity related to altitude changes which helps avoiding conflicts during climbs and descends. Flow structure captures the complexity from aircraft on intersecting paths, which can increase the risk of conflicts. Traffic mix considers the diversity in aircraft speeds, affecting spacing and separation requirements. Traffic density reflects the number of aircraft within the airspace. This dimension is important for considering high traffic densities.

The mesh approach is used for calculating all these indicators. An example of such a mesh for this complexity metric is illustrated in Figure 6. In this case, other three alternative spatial displacements are used. Therefore, the aggregate value of each indicator represents the mean value of all the mesh shifts. The time window in which the data is exported is hourly. For this complexity metric the traffic outside the area of interest is not interacting with the traffic inside the airspace. Therefore, one assumption needs to be defined. **Two aircraft can interact if and only if both of them are within the airspace of interest.**

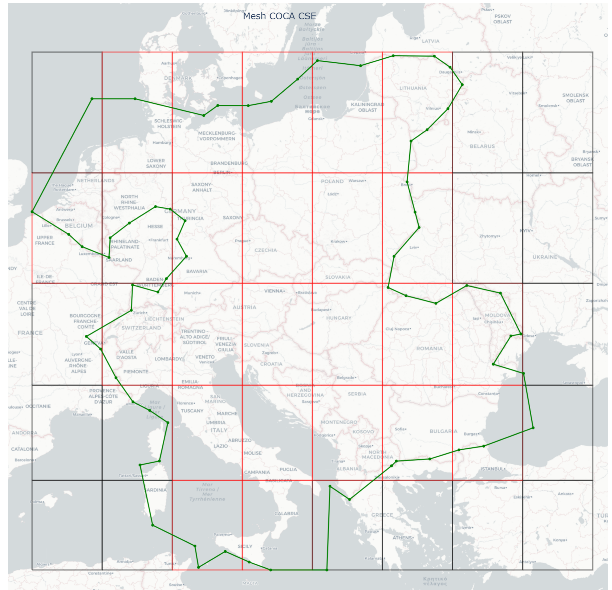


Figure 6. Mesh Applied on Largest Experiment Area (red cells are considered to be active, and black cells to be inactive)

1.1 Traffic Evolution

Traffic evolution is represented by the potential vertical interactions between aircraft. Moreover, the aircraft should be in different flight phases to be able to interact. Therefore, an assumption is needed. **A vertical interaction is considered if and only if aircraft are in different phase of the flight.** For a better understanding, let's consider the scenario presented in Figure 7. In this artificial cell, four aircraft are present. Two of them are in the climbing phase, one is descending and the other one is cruising. In this scenario, there are 10 potential vertical interactions as calculated in Equation 3.

$$\text{Vertical Interactions} = 2 \cdot C + 3 \cdot Cr + 3 \cdot D = 10 \quad (3)$$

Here, C is the number of aircraft in climbing phase, Cr in cruising phase, and D in descending phase.

The two climbing aircraft can interact with the cruising and descending aircraft. The descending aircraft can interact with the cruising aircraft and both climbing aircraft. The cruising aircraft can interact with both climbing aircraft and the descending aircraft.

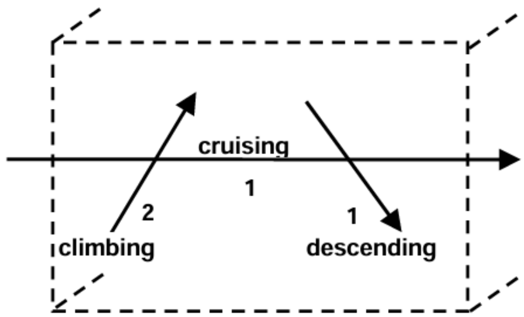


Figure 7. Potential Vertical Interactions [33]

In the scenario described above, the number of potential vertical interactions is 10. However, this number can be thought as the interaction potential over time as well. In this matter, it can be estimated how much time aircraft within a specific cell might be at risk of vertical interaction with each other. Therefore, an overall indicator, noted with VDIF, can be computed in a given period of time within a specific cell, by using the mathematical formula shown in Equation 4. It represents the ratio of the expected duration of all potential vertical interactions in all the cells divided by the total flight hours within the cell.

$$\text{VDIF} = \frac{\text{Vertical Interact. (h)}}{\text{Flight hours}} = \frac{\sum_{k=1}^{Nc} V_k}{\sum_{k=1}^{Nc} T_k} \quad (4)$$

Here, V_k represents potential vertical interactions in hours for each cell and T_k the time flown of all the aircraft of cell k in one hour. Nc represents the storage of all active cells.

1.2 Flow Structure

Flow structure can be explained by potential horizontal interactions. By analysing these potential horizontal interactions, the flow structure of the traffic can be better managed. Therefore, these interactions occur when aircraft paths cross or converge on the same horizontal plane. More than that, a horizontal interaction between aircraft happens when their headings are different. Actually, the difference between headings should be greater than 20°. For that, the following assumption is considered. **A horizontal interaction between two aircraft is considered when the difference of their headings is larger than 20°.**

For example, a scenario based on five aircraft is shown in Figure 8. Aircraft a and b follow the same track. Apart from aircraft a and b, it is noted that all the difference in headings are greater than 20°. In this case, there are 18 potential horizontal interactions as calculated in Equation 5.

$$\text{Horizontal Interactions} = 3a + 3b + 4c + 4d + 4e = 18 \quad (5)$$

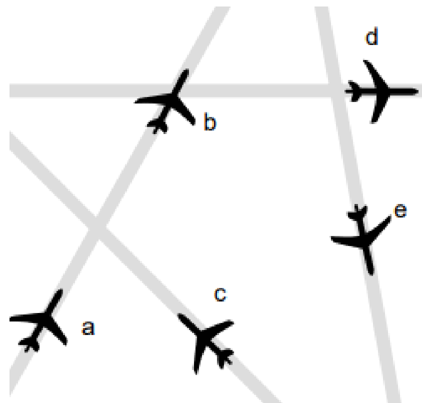


Figure 8. Potential Horizontal Interactions [33]

In the same manner as VDIF, this complexity indicator can be calculated over time. Noted with HDIF, the potential horizontal interactions expressed in flight hours can be computed using Equation 6.

$$\text{HDIF} = \frac{\text{Horizontal Interact. (h)}}{\text{Flight hours}} = \frac{\sum_{k=1}^{Nc} H_k}{\sum_{k=1}^{Nc} T_k} \quad (6)$$

where H_k is the potential horizontal interactions expressed in hours in cell k, T_k is the time flown of all the aircraft of cell k in one hour, and Nc represents the storage of all active cells.

1.3 Traffic Mix

Traffic mix refers to the variety of aircraft operating within same airspace. It can includes differences in aircraft types, sizes, and speeds. Potential speed interactions arise when aircraft with different speeds are present in the same time within the airspace area. This leads to possible situations where faster aircraft may need to overtake slower ones. Affecting the required separation, the complexity in managing air traffic may increase. For example, two aircraft are flying on the same track at the same level with a safe separation between them. The leading aircraft is a Bombardier Dash 8. The cruise speed of this aircraft is 0.61 Mach which is approximately 360 kts. Behind him, a Boeing 737 is flying with a speed of 0.78 Mach, which represents almost 450 kts. In this scenario, the Boeing 737 is faster than the Bombardier Dash 8. It illustrates a traffic mix scenario where speed differences require careful management to maintain safe separation.

Therefore, speed interactions influences the dynamics of aircraft separation and the workload of the air traffic controllers. However, in this study a potential speed interaction is considered when the difference in speed is greater 35 kts. A speed difference of 35 knots or more is significant enough to impact separation and spacing. Thus, an assumption is made based on this threshold. **It is considered potential speed interaction if the speed difference between aircraft is greater than 35 kts.** Over time, this complexity indicator, noted by SDIF, can be calculated using Equation 7.

$$\text{SDIF} = \frac{\text{Speed Interact. (h)}}{\text{Flight hours}} = \frac{\sum_{k=1}^{Nc} S_k}{\sum_{k=1}^{Nc} T_k} \quad (7)$$

where S_k represents potential speed interactions expressed in hours in cell k, T_k is the time flown of all the aircraft of cell k, and Nc represents the storage of all active cells. The variables are calculated hourly.

1.4 Traffic Density

Traffic density is highly correlated with flight interactions. The more aircraft are within a given airspace volume, the higher likelihood that their flight paths will intersect, leading to potential interactions. Basically, traffic density serves as an indicator of how frequently potential conflicts might occur. Adjusted density is a more precise complexity indicator for traffic density because it accounts not just for the number of aircraft in a given volume but also for their distribution and interactions. By using the mesh, this indicator reflects more accurately the operational complexity of the airspace.

Let's imagine two airspace sectors as presented in Figure 9. Sector A has 10 aircraft spread evenly throughout the sector. Sector B also has 10 aircraft, but they are concentrated in the upper part of the airspace. If the number of aircraft is measured, in this case 10 aircraft, both sectors seems equally complex. However, adjusted density would show that sector B is more complex because it accounts for the concentrated distribution of aircraft. It has the higher likelihood of interactions. In contrast, sector A would have a lower adjusted density due to the lack of potential conflicts. If adjusted density is expressed mathematically, the complexity indicator, noted by AD, represents the ratio between potential interactions in hours and flights hours. This is shown in Equation 8.

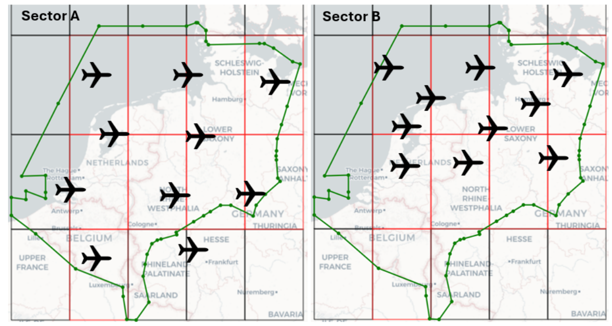


Figure 9. Flight Distribution in Two Different Scenarios across MUAC

$$\text{AD} = \frac{\text{Interact. (h)}}{\text{Flight hours}} = \frac{\sum_{k=1}^{Nc} D_k}{\sum_{k=1}^{Nc} T_k} \quad (8)$$

where D_k is the expected duration of potential interactions in one hour, T_k is the sum of the time flown in cell k, and Nc represents the storage of all active cells.

1.5 Complexity Score

To provide a single, unified metric that integrates the combined effects of all types of interactions, a complexity score is calculated. The computation of this complexity score can be performed by simply sum the potential vertical, horizontal, and speed interactions as suggested in Equation 9.

$$\text{Complexity Score} = \text{VDIF} + \text{HDIF} + \text{SDIF} \quad (9)$$

2. Air Traffic Controller Workload Metric

In general, flight interactions require careful monitoring and managing air traffic within the airspace.

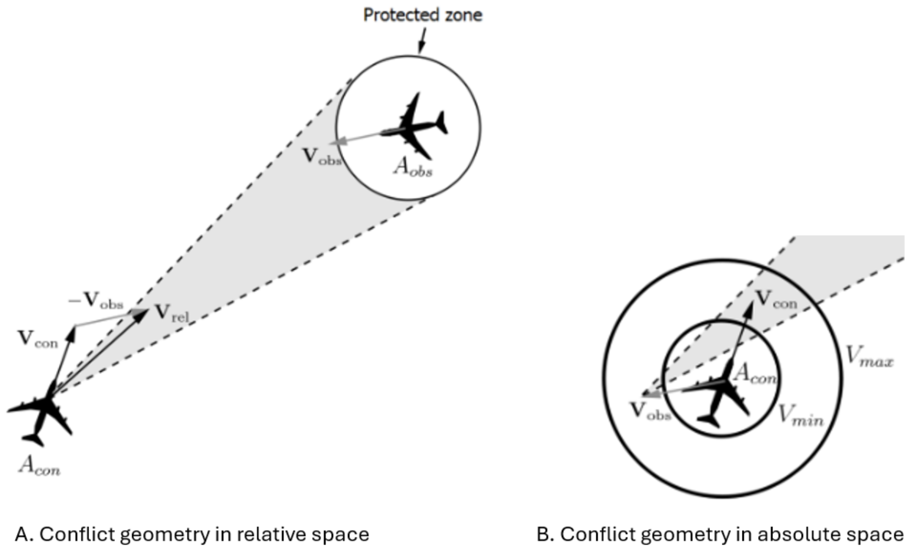


Figure 10. The Solution-Space Diagram Concept [34]

This can result in increasing the air traffic controllers workload. As the number and complexity of these interactions increase, the demands on controllers grow accordingly. Therefore, in this study a complexity metric dedicated for assessing the air traffic controller workload is introduced. However, to assess the workload of air traffic controllers, it is essential to evaluate the complexity of their tasks. One effective method for this evaluation, as mentioned in section III, is the Solution-Space Diagram. This method quantifies the complexity of a sector by analyzing the constraints and available maneuvering space for aircraft. Basically, it shows how many options the air traffic controller has while controlling an aircraft. In general, the less options for the controller, the more complexity rises.

In this study, SSD is used for its dual benefits. Through the analytical part, it offers an overall score of complexity of the airspace. On the other hand, the visual side of the method provides a clear vision of the controller workload. Basically, for each aircraft being in control within the airspace, a SSD can be computed. The diagram is computed based on the relative positions and speeds of the other aircraft present in the airspace. Basically, for each time step, each aircraft in the airspace takes the status *controlled*, while all other aircraft within the airspace area receive the status *observed*. Further, each *controlled aircraft* form pair with each *observed aircraft*. For each pair, a conflict assessment is performed. This assessment consists of defining the relative velocity and the Forbidden Beam Zone, FBZ, of the observed aircraft. If the relative velocity vector lies inside the FBZ, then the pair is called *proximate pair of aircraft*. In the end, all the FBZs from these *proximate pairs* are transposed into the absolute space of the controlled aircraft. An example is shown in Figure 10. The detailed methodology of Solution-Space Diagram is explained in Appendix in subsection A.H.

In order to have a global indicator which measures the workload of the controller, a formula is defined. Basically, for each aircraft which is in control at time *t*, the unsafe area is calculated by using Equation 10.

$$\text{Unsafe Area}^{t}_{A_{con}} = \sum_{i=1}^{\text{Nobs}} \text{FBZ}_i \tag{10}$$

Here, unsafe area is the summation of all the FBZs of the proximate pairs formed with aircraft controlled A_{con} at time *t*.

To approximate the potential workload of the air traffic controller, a percentage value is calculated based on this unsafe area. This percentage reflects how much of the total maneuverable space is occupied by unsafe area. The individual workload index is then performed for every *controlled aircraft* at any given time t. The overall workload index is then found by summing these individual percentages and dividing by the total number of aircraft. within the airspace. The formula is expressed in Equation 11.

$$\text{Workload Index}_t = \frac{1}{n}\sum_{i=1}^{n} \text{Unsafe Area}_i \tag{11}$$

where n represents the total number of aircraft present within the airspace at time t. The final workload score is the average of these workload indexes.

At the beginning, a simplified version is computed. For this simplified SSD, only the actual speed of the *controlled* aircraft is considered. Further, this diagram is expanded. One of the limitation of this method, as mentioned in section III is the 2D representation. This approach is not considering the altitude dimension. However, in this study, this component is adding in examining the workload index. Basically, this third dimension is represented by a color which depends on the severity score. Severity score is defined based on the distance and the difference in altitude between aircraft. As visual representation, near the SSD an altitude bar is added. In this matter, all the possible options for the aircraft which in control are displayed.

2.1 Estimating the severity score

As mentioned above, this severity score gives an overview of the situation's severity. In order to compute the severity score function, few items are taken into consideration:

1) *The function should have weights.* A weighted scoring system is used to recognize that not all factors have the same impact on the severity.
2) *The function should incorporate non-linear transformation.* Using non-linear transformation highlights differences more at closer ranges than at farther ones.
3) *The function should be normalised in the end.* Normalisation of the score helps to ensure it fits within a specific range, such as 0 to 1.

Based on these rules, the severity score function is computed. Initially, an individual score based on distance and difference in altitude is calculated with Equation 12.

$$\begin{aligned} \text{score}_{\text{dist}} &= \sum_{i=1}^{N} \text{HP} - (\text{HP - LP})\left(\frac{\text{dist}_i}{\text{max}_{\text{dist}}}\right)^{0.3} \\ \text{score}_{\text{alt}} &= \sum_{i=1}^{N} \text{HP} - (\text{HP - LP})\left(\frac{\text{alt}_i}{\text{max}_{\text{alt}}}\right)^{0.3} \end{aligned} \tag{12}$$

max_{alt} and max_{dist} are defined once the airspace area is created. These values represent the biggest difference in altitude that can be found in the airspace and the largest distance in the area of interest. At the beginning, severity is classified into four categories, from 1 to 4. Visually, one is represented by green, 2 by yellow, 3 by orange, and 4 by red. Therefore, HP represents the maximum score, 4, which presents the highest priority. LP is the scaling factor and it is set to 3. This is used to ensure that the score varies within a predefined range, from 1 to 4 in this context. $dist_i$ represents the distance between aircraft while alt_i is the difference in altitude between aircraft. Ultimately, N is the number of aircraft within the airspace.

Once the individual scores are computed, the weights are assigned. In this study, the values $w_d = 0.4$ and $w_a = 0.6$ are used, where w_d is the weight assigned to the distance. w_a is the weight assigned to the altitude. Now, the intermediate severity score function is defined as in Equation 13.

$$\text{Weighted Score} = w_d \cdot \text{score}_{\text{dist}} + w_a \cdot \text{score}_{\text{alt}} \tag{13}$$

where $\text{score}_{\text{dist}}$ and $\text{score}_{\text{alt}}$ are defined in Equation 12. Finally, the normalized severity score function is presented in Equation 14.

$$\text{Severity Score} = \frac{\text{Weighted Score} - 1}{\text{HP - LP}} \tag{14}$$

where HP is the maximum score, 4, LP is the scaling factor, 3, and Weighted Score is computed in Equation 13. For each category, a range of values is defined. Table 2 shows the computation of these ranges.

Table 2. Severity Categories

Category	Values Range
Green Category	[0, threshold - 0.2)
Yellow Category	[threshold - 0.2, threshold - 0.1)
Orange Category	[threshold - 0.1, threshold)
Red Category	>= threshold

The threshold parameter is determined by computing the severity score where the distance is the minimum horizontal standard separation, 5 NM, and the difference in altitude equals the minimum vertical standard separation, 1000 ft.

2.2 Control penalties and anomalies
Loss of separations or anomalies may appear in the traffic scenarios. To account for those, several conditions are implemented.

- *Determining a penalty score*. If two aircraft are losing the standard safety separation, then the on-board system will resolve the conflict (e.g TCAS), so no air traffic controller procedures needed. Since, this represents a failure or managing air traffic by the controller, a penalty score is associated.
- *Separating the parallel aircraft*. For example, two aircraft are flying vertical parallel. This limits the FBZ estimation because the safety circles coincide on an horizontal perspective. In order to eliminate this limitation, an extra variable is added. This variable keeps track of these pairs and does not necessarily increase the workload of the controller.

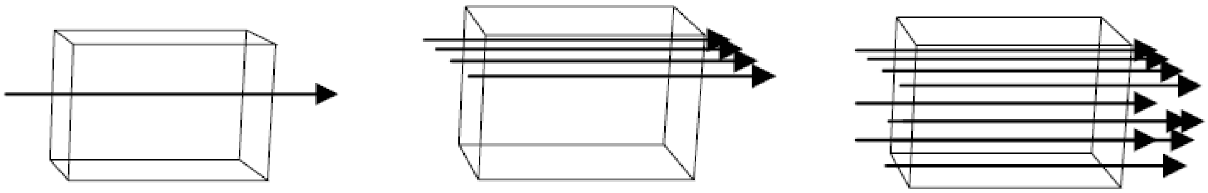
3. Operational Environment Complexity Metric
The dynamics within the airspace are captured by dynamic density model. The workload of the air traffic controller based on the airspace activity is expressed with the SSD approach. In addition to this, the last metric used in this study is representative for estimating the complexity of the traffic flows and patterns. As presented in section III, using fractals, the complexity of the airspace can be estimated. Moreover, with this method, the comparison between FRA and the network of ATS routes can be captured better.

To illustrate an example, let's consider three scenarios which are presented in Figure 11. The first scenario is described by flights which are flying on the same track on a single altitude. This scenario is displayed in Figure 11a. Based on the traffic pattern, the fractal dimension of this scenario is equivalent with 1. They do not change the altitude, neither direction. In Figure 11b, the second scenario is presented. In this case, the flights are flying on a single altitude, but different tracks. Due to change of direction, in this case the dimension is considered to have value 2. Figure 11c represents a more real scenario because here the flights are using different altitudes and different tracks. Since, there are changes in altitude and direction, the dimension is 3.

To capture the traffic patterns better, the mesh is used for this metric. Compared to the dynamic density model, the dimension of the cells within the mesh are changing every simulation. At the beginning, a number of scales is defined. Based on this number, the side-length is determined and calculated. For each scale, the Box Counting Method is applied. Basically, this technique counts the boxes which contains flights of each mesh. An example of applying this method is shown in subsection A.I.

3.1 Box Counting Method
The Box Counting Method is a mathematical technique used to estimate the fractal dimension of a geometric structure. It is widely used because it is relatively straightforward and can be applied to both theoretical fractals and real-world data such as coastlines, cloud boundaries, or airspace activity. Initially, this technique involves a mesh overlay. As mentioned before, the mesh is used and it is overlaid over the airspace area. The dimensions of the cells of the mesh are big. Once, the mesh is computed, it is counted the number of cells that contain parts of the flights. This number is denoted as N_l, where l is the size of the cell. This process is repeated with progressively smaller cells, allowing for a more detailed capture of the structure's intricacies.

Further, it is plotted the logarithm of the number of non-empty cells $log(N_l)$ against the logarithm of the cell size $log(1/l)$. To quantify the relationship between $log(N_l)$ and $log(1/l)$, a linear regression



(a) Aircraft flying one route single altitude **(b) Aircraft flying one altitude different altitudes** **(c) Aircraft flying different routes different altitudes**

Figure 11. Examples Dimensions in En-Route Environment[31]

model is applied. This linear regression model finds the best-fitting line through the data points observed on the plot. An example is shown in Figure 12. The slope of the line in this plot gives the fractal dimension *FD*, according to the relationship showed in Equation 15. In real-world scenarios, data may not perfectly align with theoretical expectations due to noise, irregularities, or finite sampling sizes. A regression model helps to mitigate these issues by providing the best linear approximation to the observed data points.

$$FD = \lim_{l \to 0} \frac{\log(N_l)}{\log(\frac{1}{l})} \tag{15}$$

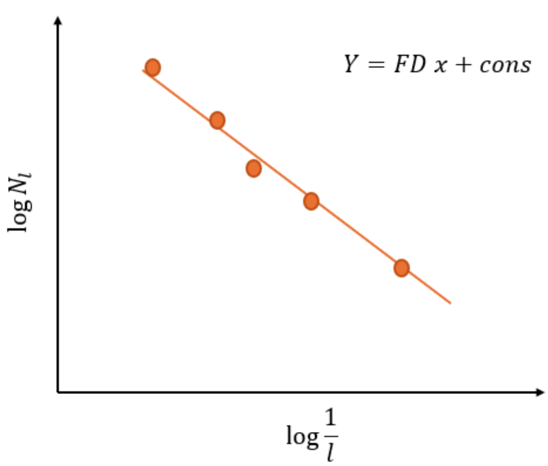


Figure 12. Computing Fractal Dimension by using Regression Models

3.2 Fractal Dimension Index

Applying the theory of Box Counting Method, in this study, a fractal dimension is calculate every time step. For each time step, an individual dimension is computed according to Equation 16.

$$D_t^s = \sum \text{cells which contain flights} \tag{16}$$

where t represents the time step and s the current scale. To avoid the boundary effect, a mesh displacement is needed. The displacement in made horizontally and vertically. In the end, the fractal dimension of the scale s is the average of all the displacements at a given time t. Equation 17 expresses this fractal dimension.

$$D^s = \sum_{i}^{Dis} D_{t_i}^s \tag{17}$$

where Dis is the displacements of the mesh. $D_{t_i}^s$ is the fractal dimension calculated using Equation 16 at time t when the mesh had the displacement i for the scale s.

Then, the overall fractal dimension, *FD*, is calculated by using the linear regression model displayed in Figure 12.

E. Post Analysis Phase

In the end, in this study, three complexity metrics are computing the model. These metrics are calculated during several simulations where different parameters of the airspace are changed. After the simulation, the data is collected for a post analysis process.

The environment point of view is added to the study because while increasing the demand, it is important to limit the environmental impact. This assessment focuses on estimating CO_2 emissions at the airspace level. This provides a clear indication of the environmental footprint associated with increased air traffic. Therefore, a briefly model of CO_2 emissions is computed. In this model, only the flights which are present in all three airspace areas analysed are considered. Moreover, a new database is integrated in the system. To estimate emissions per flight, the calculations are performed depending on the aircraft types. Therefore, the specific fuel consumption rates based on the aircraft types are imported from the performance database of EUROCONTROL. In addition to this, the distance flown by each flight is calculated. With this data, the calculation of flight duration is defined by Equation 18.

$$\text{Flight Duration}_i = \frac{\text{Distance Flown}_i}{\text{Average Cruise Speed}_i} \quad (18)$$

where i represents each aircraft in the model. By having the flight duration, the total fuel burned is computed by multiplying with the fuel consumption rate. The formula of the Total Fuel Burned is shown in Equation 19.

$$\text{Total Fuel Burned}_i = \text{FCR}_i \cdot \text{Flight Duration}_i \quad (19)$$

where FCR represents the Fuel Consumption Rate expressed in kg/h. The Total Fuel Burned indicator is expressed in kg. The last step in the model is to convert the fuel burned into CO_2 emissions. It is known that aviation fuel has a CO_2 emission factor. Typically, burning 1 kg of aviation fuel produces about 3.15 kg of CO_2. Therefore, the final formula of the model is presented in Equation 20.

$$\text{CO2 Emissions}_i = 3.15 \cdot \text{Total Fuel Burned}_i \quad (20)$$

To compute and estimate an overall CO_2 emissions indicator, the summation of all the CO2 Emissions_i is needed as presented in Equation 21.

$$\text{CO2 Emissions Index} = \sum_{i}^{N} \text{CO2 Emissions}_i \quad (21)$$

V. Experiment Design

A. Hypotheses

Before starting simulating, few hypotheses are set. These hypotheses serve as guiding questions that help to focus the research and its objectives.

H1: The airspace usage under FRA is more extended than under the network of ATS routes.
FRA allows aircraft to fly direct routes instead of being confined to fixed paths. Therefore, the airspace usage under FRA should be more extensive than with traditional ATS routes.

H2: The level of air traffic controller workload increases due to the creation of invisible hot spots on the map under the FRA operational environment.
When airlines choose free and direct routes, unexpected trajectory intersections may occur. In ATM environment, this intersections are called invisible hot spots. Basically, in the ATS routes network, air traffic controllers are aware of where flight paths intersect because these points align with route intersections. However, in the FRA environment, controllers face the challenge of identifying these intersections. This additional challenge may increase the workload of the air traffic controller.

H3: Managing high demands of free routes in a larger airspace area significantly increases its complexity.
Applying FRA to larger airspace areas is likely to increase complexity. This is due to the challenges of coordination and cooperation in a big environment with extensive air traffic and multiple invisible hot spots.

H4: Due to free flight, the number of flight interactions is smaller in the FRA environment than in the ATS Routes Network environment.
It is expected that the number of flight interactions is smaller under FRA compared with the ATS routes system. This is because flights following traditional fixed routes require more often changes in track.

H5: An airspace operating under ATS routes

structures has a smaller complexity compared to an airspace operating under FRA.

In general, an operational environment with fixed routes is more structured and organised than a FRA environment. This is because it consists of predefined, fixed pathways that aircraft must follow. Moreover, the air traffic controllers should be familiar with these routes making it easier to predict and manage traffic patterns.

H6: The footprint of CO_2 emissions for the FRA environment is smaller than the one for ATS Routes Network.

The footprint of CO2 emissions for the FRA environment should be smaller than that for the ATS Routes Network because FRA allows aircraft to fly more direct and optimized routes. More than that, this should reduces the flight distance lowering the fuel consumption and, consequently the CO_2 emissions.

H7: The complexity score for FRA is consistently lower than that for the ATS Routes Network across all demand levels studied in this paper.

It is expected that the free flight simplifies the air traffic management under all levels of demands proposed in this study.

B. Simulation Environment

BlueSky ATM Simulator is used to evaluate and validate the hypotheses mentioned aboved. The simulation model described in section IV is integrated in this open-source ATC simulator. This application is developed by students and researchers at the Aerospace Engineering Faculty at the Delft University of Technology.[35]. Figure 13 shows a snapshot of the BlueSky Application when running a scenario. BlueSky uses a modular architecture based on the Python programming language. The program execution is based on two important modules, namely the Simulation Control, *sim*, and the Command Stack module, *stack*. Furthermore, the actual traffic simulation is handled by the Traffic module, *traf*. This module integrates all the aircraft data related to the simulated traffic. It also includes the performance and navigation databases.[36] As well, several functions for aerodynamics and navigation calculations are present in BlueSky software.

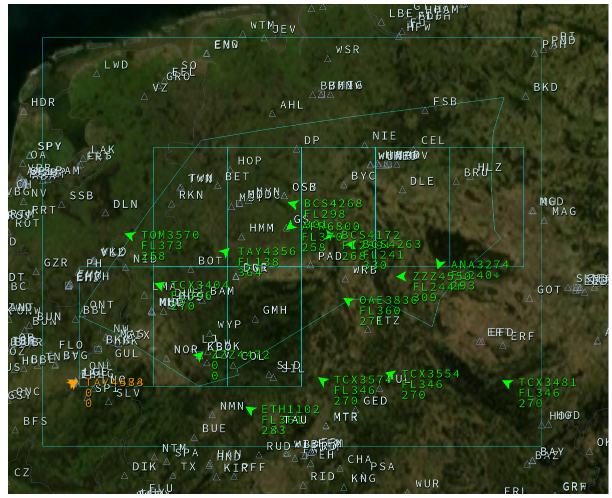


Figure 13. Snapshot of BlueSky Application

For the thesis purposes, a plugin has been built in addition to these modules. This plugin provides the calculation of different complexity metrics. The plugin is called *complexity* and consists of four stack functions. The *AIRSPACE* function is used in order to create the airspace area. If this function is not called at the beginning, all the complexity metrics are not available. Once the airspace is created, there are three complexity metrics available. The *COCA* function is dedicated for the Dynamic Density model, while the *WLSSD* function captures the Solution-Space Diagram approach. The last stack function, *FD* is used to measure the fractal dimension of the traffic scenarios. All these models are based on the theory described in section IV. The details of all the stack functions of the plugin are briefly described in subsection A.J.

As mentioned in subsubsection IV.C.2, some complexity metrics are evaluated by using a mesh. In this study, the grid approach is used to evaluate flight interactions and airspace structure. Each airspace dispose of specific cells parameters. For example, the smallest airspace, *HAN*, has cells of 1 degree in latitude and longitude with a height of 4500 ft. The medium-size airspace, *MUAC*, employs a mesh with a horizontal parameter of 2 degrees and a vertical parameter of 4500 ft. The largest airspace,*CSE*, has a mesh with the size of cells of 4 degrees latitude and longitude and 4500 ft height. These parameters are chosen based on the computer performance and relevance to the project. These parameters are illustrated in Figure 29a, Figure 29b, and Figure 29c.

For dynamic density model, three extra spatial displacements are applied. When the fractal dimension model is computed, five displacements are used. Notably, for fractal dimension technique, the shifts included adjustments in altitude, unlike dynamic density model where no altitude shifts are made. The parameters for each shift are summarized in Table 18 and Table 19 in Appendix subsection A.C.

To set up the simulation and evaluate the complexity of the airspace, three independent variables and four dependent variables are chosen. The independent variables are the key factors that influence the dependent variables. Moreover, this setup is used to understand the effects of the independent variables on the dependent ones.

C. Independent Variables

When talking about capacity, the physical size of the airspace plays an important role. In larger airspace areas, controllers have more room to separate and manage aircraft, which can reduce the frequency of interactions and potential conflicts. However, larger areas can also increase the complexity of coordination, especially if traffic is unevenly distributed. Therefore, to test these effects, the first independent variable introduced in the model is characterised by the size of the airspace. Three airspace areas are evaluated in this study. All three areas have different dimensions as described in subsubsection IV.B.1. The analysis starts with the smallest airspace which is defined by the boundaries of the sector group of MUAC airspace, namely Hannover Sector Group. This airspace is chosen because it provides a clear example of the challenges associated with managing air traffic in a highly concentrated airspace. For the medium-size airspace, MUAC is the second area which is analysed. As a medium-sized airspace, it offers a manageable level of complexity that is ideal for testing and analyzing air traffic management strategies. A fictive airspace area is chosen as the largest size which includes a big part of the European airspace. This choice encompasses a vast and diverse range of traffic flows, making it an ideal case for studying large-scale air traffic management. In this study, this airspace area is noted by CSE.

The level of demand is chosen as the second independent variable because it directly influences the traffic flow and airspace capacity. This variable has three conditions: normal, high, and super high demand. The definition of demand is obtained from the theory explained in subsubsection IV.C.4. Normal demand is defined as the actual demand of traffic. High demand and super high demand are computed based on the normal demand. High demand adds 50% extra flights randomly on top of the normal demand. Super high demand almost doubles the flights from the normal demand.

Lastly, the third independent variable of the study is the mode of operating within the airspace. This variable is divided into three types, namely direct routes, fixed routes, and a mixture between direct and fixed routes. Direct routes creates the Free Route Airspace scenario. Fixed routes defines the scenario based on ATS Routes Network. For a reference point, the actual scenario is used which represents the mixture of direct and fixed routes. Once the independent variables are defined, the computation of scenarios starts. A scenario represent a combination of all three independent variables. For example, scenario 1 has normal demand within MUAC airspace following fixed routes. Figure 14 shows the combination of the independent variables of the model.

D. Dependent Variables

In order to complete the model, several dependent variables need to be considered. These variables are affected by the independent variables proposed in this study. The complexity metrics described in section IV represent the dependent variables. Basically, when assessing the complexity of a certain airspace, four elements are evaluating, namely traffic density, flight interactions, air traffic controller workload, and traffic patterns. All four variables directly reflect the outcomes and effects of changes in airspace characteristics, such as size, demand and operational mode. These variables respond to the conditions set by the independent variables. The

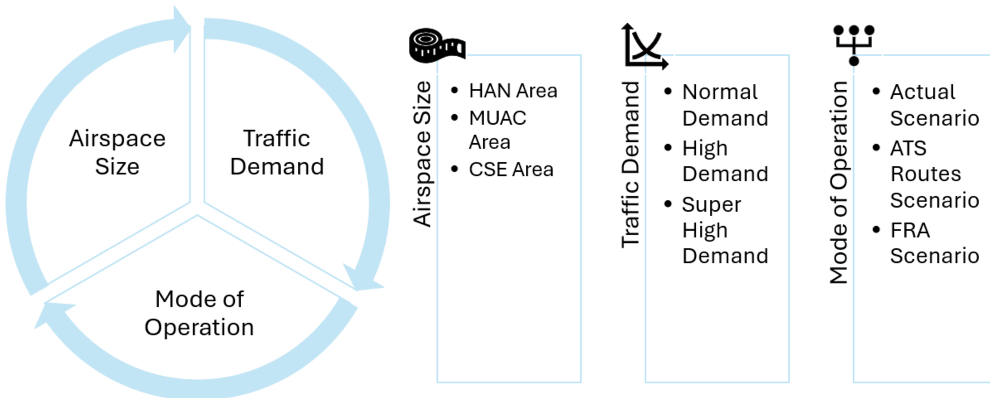


Figure 14. Independent Variables

description of each dependent variable can be found in Table 3.

Traffic density is chosen because it depends on factors like airspace size and demand and can affect the airspace capacity. High traffic density can lead to increased complexity and the potential for conflicts. Moreover, flight interactions influence the overall air traffic complexity because with higher traffic density and more complex airspace structures, the number of interactions may increase. Air traffic controller workload variable is important to considered in this study because it highly depends on the number of aircraft, the complexity of their interactions, and the airspace structure. High workload can affect safety and efficiency. Making a comparison of fixed and direct routes, traffic patterns is chosen as dependent variable. Changes in operational modes or demand can alter these traffic patterns.

Going into more detail, these dependent variables are characterised by some complexity indicators which are displayed in Table 25, Table 26, Table 27, and Table 28. These complexity indicators can be divided in three categories.

- **Airspace Activity**: In this category, the indicators are exported every time step and they describe the traffic evolution, flow structure, traffic phase, and the presence of proximate pairs. This category gives an overview of the activity within the airspace.
- **Dynamic Activity**: This category includes variables that are calculated on an hourly basis, providing a clearer overview of how traffic is dispersed throughout the airspace and what are the possible interactions among them.
- **Controllers Activity**: In this category, the complexity indicators are estimated every 10 minutes, based on the traffic situation and conflict detection. The choice of 10 minutes is made based on the balance between airspace traffic and air traffic controller activity.

Table 3. Dependent Variables

Dependent Variable	Description
Traffic Density	Number of aircraft in the airspace area of interest.
Flight Interactions	Situations where aircraft paths may intersect or come close to each other. It represents the possible interactions between flights.
Air Traffic Controller Workload	Level of effort required by air traffic controllers to manage air traffic within a specified airspace.
Traffic Pattern	Flow and organization of air traffic within the airspace.

E. Traffic Scenarios

The first step in creating the scenario is to define the plugin and specify the metrics to be calculated. Next, the scenario is populated with traffic data. Initially, the final set of flights is sorted by the time column. The earliest flight on the selected date is assigned a simulation time of 00:00:00, and all other simulation times are calculated based on this reference point. To create a flight into simulation, three steps are needed. First, the aircraft is created using the command *CRE*. There are two types of flights: those preparing for departure and those already airborne at the start of the simulation. Next, the flight trajectory is added with the *ADDWPT* command. Finally, vertical and lateral navigation are enabled using the commands *VNAV ON* and *RTA*.

Due to computational constraints and performance considerations, a scenario was created for each combination of independent and dependent variables. Additionally, dynamic density was measured using four different mesh shifts, which is the most time-consuming metric. As a result, separate scenarios were created for each mesh. In total, for each airspace, demand level, and airspace structure, six scenarios were generated, leading to a total of 162 scenarios. Table 4 shows the scenario settings.

Table 4. Scenario Setting

Airspace	Number of simulations	Time frame of simulation
HAN	54	23 hours
MUAC	54	23 hours
CSE	54	9 hours

VI. Results

After running the simulations, all the exported data is integrated in the post-analysis process. In the end, all the results are grouped in an interactive dashboard. At the beginning, the data is verified to ensure that there is no discrepancy. In order to achieve this, the Opening Area Time variable is computed. This variable consists in monitoring the airspace. When at least one aircraft is flying within the airspace area, the variable is turning 1. If there is no aircraft flying within the airspace, the variable is set to 0. Therefore, for all three airspace areas, it can be validated that each airspace area is continuously open during the entire simulation. For more information, this variable is detailed in Appendix subsection A.L.

A. Airspace Overview

Before delving into the complexity metrics, it is important to have an overview of the traffic within the airspace. Therefore, the entry counts indicator measures the static density during a given period of time. It is defined as the number of flights entering in the sector during a selected time period. This period is called Hourly Entry Count time period. Figure 15 shows the entry counts of MUAC airspace for a normal demand. It can be seen that there are fluctuations in traffic volume throughout the 23-hour period. There are several peak hours throughout the day, including 05:00 - 06:00, 09:00 - 10:00, 12:30 - 13:30, and 19:00 - 20:00. Among these, the 09:00 - 10:00 period experiences the highest congestion, as traffic density remains consistently high throughout this entire hour. Identifying the peak hours may help in planning the management strategies and the resource allocation better.

Looking into Appendix in Figure 64 and Figure 65, it is observed that FRA entry counts are generally lower than those of Actual and ATS across all demand types. However, the trend remains consistent, indicating that even with fewer aircraft in the airspace, peak times remain unchanged. The same results hold for the other two airspace areas, for all demand types. The overall entry counts for all the independent variables are displayed in Appendix subsection A.L in the section *Entry Counts*.

To analyse the behavior of the traffic, the traffic phase variable is computed. This variable indicates whether traffic is vertically dynamic within the airspace. Basically, this means the altitude changes of traffic during transiting the airspace area. Based on the assumptions of the study, there are three possible phases in an en-route environment: climb, cruise, and descent. These phases are determined by the aircraft's vertical speed. For instance, in the HAN airspace under normal demand, the traffic phase distribution is illustrated in Figure 17. It can be observed that most of the traffic is in the cruise or climb phase. The dashed lines represent the descend phase and they

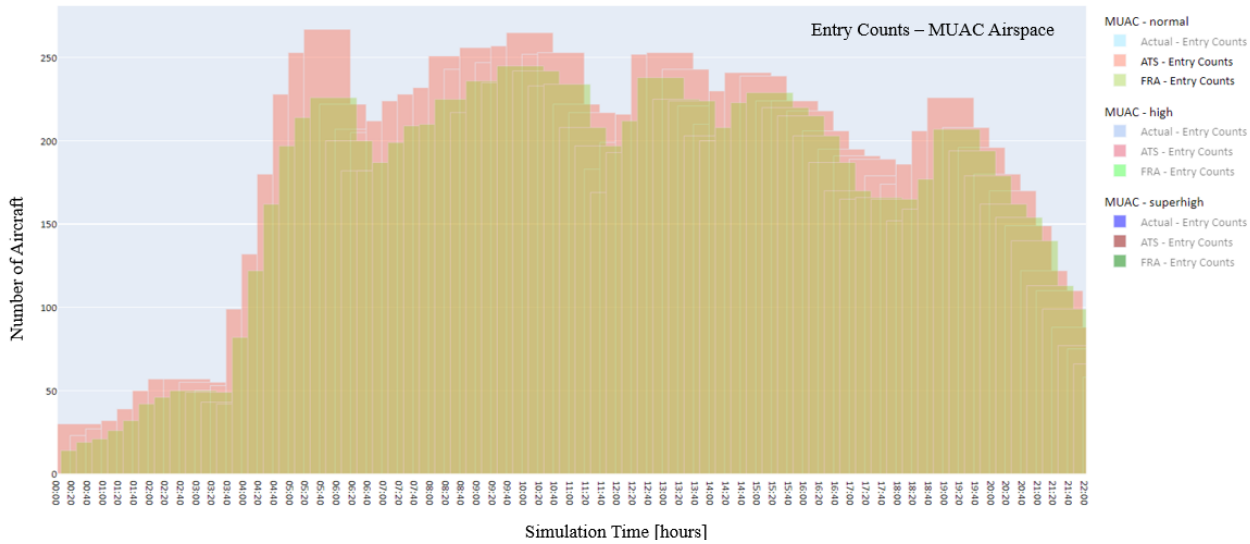


Figure 15. Entry Counts - MUAC Airspace

are much lower than the rest.
For a better illustration, in the same airspace in a normal demand, flights under FRA are highlighted in Figure 16. Here, it can be observed that the airspace has a mixture of cruising and climbing traffic. In addition to this, a dedicated parameter which measure the mixture of traffic phases is calculated. This variable indicates whether the traffic is mixed in phases. The range of this variable is between 0 - 100, where 100 means highly mixed. This indicator is computed based on [17] by Equation 22.

$$\mathrm{MIX} = \frac{200}{9}\big(c1(16c1^3 - 32c1^2 + 11c1 + 5) + de(16de^3 - 32de^2 + 11de + 5)\big) \tag{22}$$

where cl represents the number of flights in climb phase and de the number of flight which are descending. During all the simulations, this coefficient presents values between 45 - 70, which means that the traffic mixture is moderate to severe. When comparing the airspace structures, the highest values of traffic mix correspond to FRA. Table 5 highlights this aspect.

Table 5. Traffic Mix Indicator - HAN

Airspace Structure	Normal	High	Super High
Actual	47	45	43
ATS	48	47	44
FRA	56	55	57

This means that giving the freedom to the airlines to plan their routes can increase the mixture in the airspace. The overall indicator for each analysed airspace area can be found in Appendix subsection A.L in the section *Traffic Phase*.

B. Traffic Dynamic

To estimate the level of complexity on the airspace level better, it is essential to analyse the level of dynamic density in the traffic. Moreover, using a mesh over the airspace, it can be determined which part of the airspace is more congested. The dynamic density is measured by the amount of interactions among the aircraft. Previously, there are mentioned several peak hours. However, there is no clear image of how the traffic is spread. So, in addition to this, the dispersion of traffic can be visualised by using the mesh. For instance, when looking at the largest airspace, CSE, it can be seen in Figure 18 that at FL300 in the Free Route Airspace at 09:00, flights

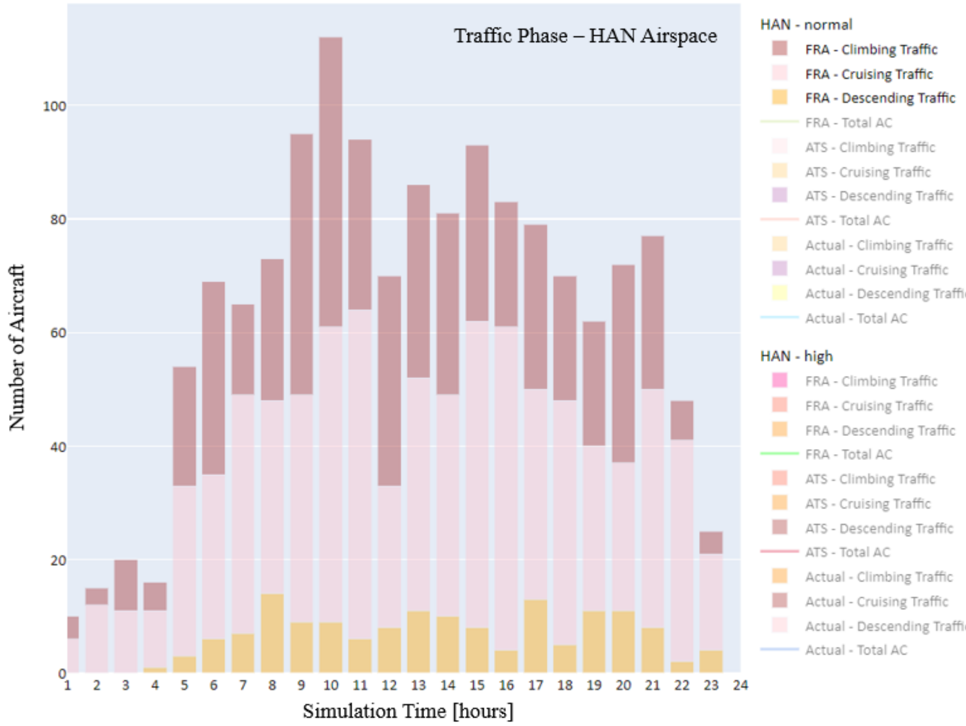


Figure 16. Traffic Phase - HAN Normal Demand FRA Airspace Structure

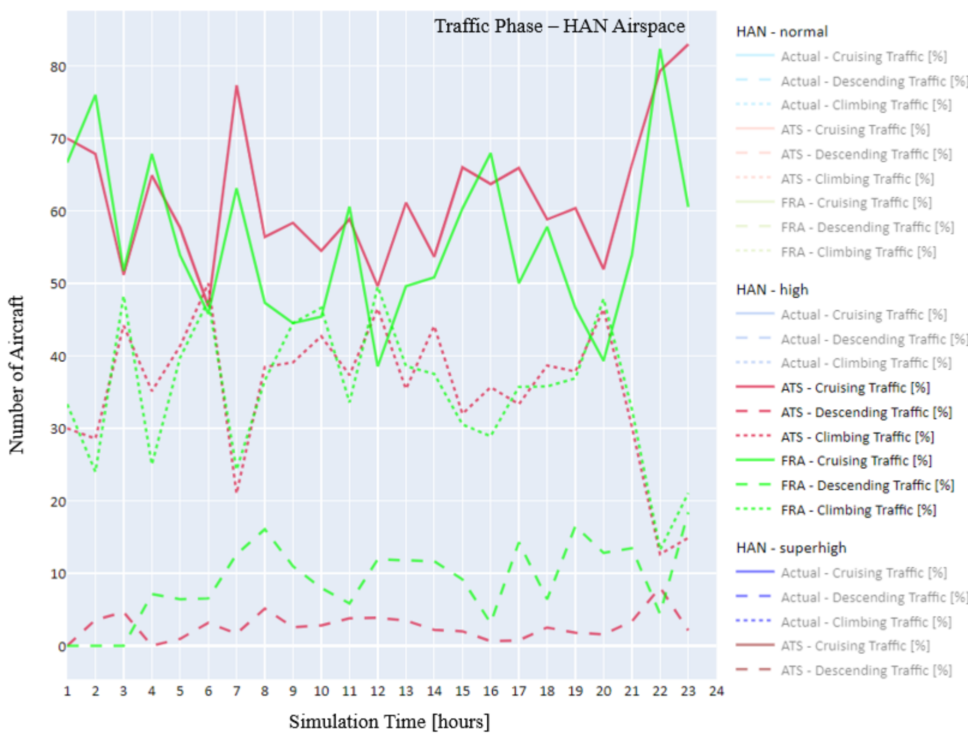


Figure 17. Traffic Phase [%] - HAN Normal Demand FRA Airspace Structure

are more evenly spread throughout the airspace compared to the traditional ATS Routes Network. While the traffic is more condensed in the East part of CSE on ATS Routes scenario, in FRA scenario the traffic is more evenly distributed over the entire airspace.

In order to analyse the distribution of the traffic in a mathematical approach, the estimation of adjusted density is used. For example, Figure 19 considers HAN airspace with normal demand. Despite of the operational activity, the indicator measures similar trends. However, once the demand increases, the adjusted density presents different results. Figure 20 compares HAN with MUAC airspace areas on super high demand. When operating in small airspace with super high demand, FRA has the highest value for the adjusted density. This indicates that air traffic is concentrated. However, as the airspace size increases, the adjusted density for both fixed routes and a mix of fixed and free routes rises significantly, nearly reaching the values for FRA. While the value for FRA slightly increases, the ATS routes and actual scenarios double their values. This means that in smaller airspace, the fixed routing or mixing free and fixed routes results in better traffic distribution.

Table 6. Dynamic Density Complexity Scores - Normal Demand

Airspace Area	Scenario	Complexity Score
HAN	ATS	0.132
HAN	FRA	0.127
MUAC	ATS	1.257
MUAC	FRA	1.009
CSE	ATS	2.812
CSE	FRA	2.111

Moreover, as mentioned previously, the adjusted density is highly correlated to the flight interactions. This can be explained by the correlation chart found in subsection A.G in Appendix Figure 39. Adjusted Density is highly correlated to horizontal interactions and there is a high correlation between horizontal and speed interactions. Based on these flight interactions, the overall complexity score per scenario is computed. Table 6, Table 7, and Table 8 include all the global complexity scores over the airspace areas.

Table 7. Dynamic Density Complexity Scores - High Demand

Airspace Area	Scenario	Complexity Score
HAN	ATS	0.313
HAN	FRA	0.288
MUAC	ATS	1.084
MUAC	FRA	1.015
CSE	ATS	3.297
CSE	FRA	3.095

On a global level, ATS routes scenarios present higher complexity than the FRA scenarios. However, in smaller airspace the level of complexity increases under FRA more than under ATS routes when the traffic demand is high or super high. This means that free flights increases the challenges of the airspace. For a better visualisation of the results, Figure 36, Figure 37, and Figure 38 display the plots of the complexity score at the smallest airspace area.

Table 8. Dynamic Density Complexity Scores - Super High Demand

Airspace Area	Scenario	Complexity Score
HAN	ATS	0.355
HAN	FRA	0.504
MUAC	ATS	1.232
MUAC	FRA	0.926
CSE	ATS	3.784
CSE	FRA	2.883

C. Air Traffic Controller Workload

Among several factors, air traffic controllers estimate their workload based on the number of aircraft they control in the same time and also the number of possible conflicts within the airspace. For this representation, let's consider the peak hour from 09:00 to 10:00 and let's analyse the workload of the controller during this time. However, before starting the evaluation, it is important to establish if there is a correlation between the number of aircraft and

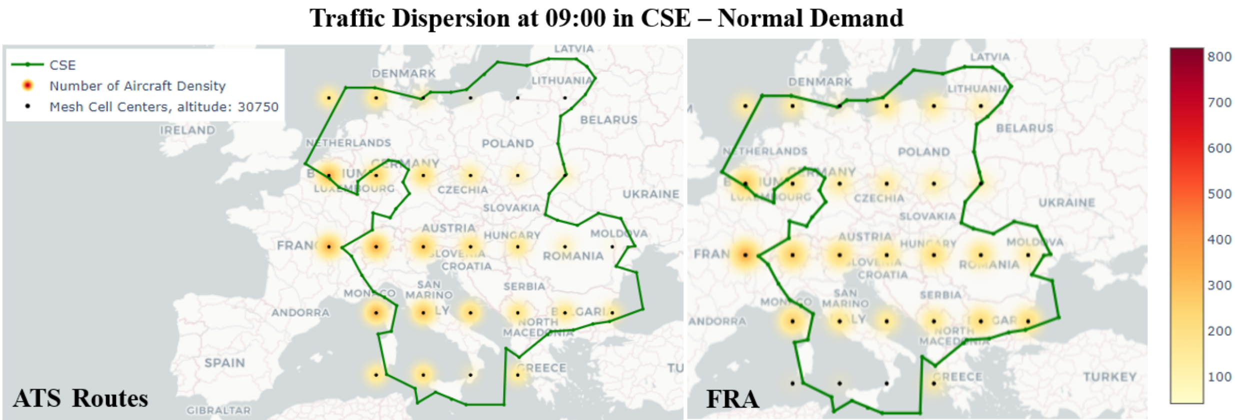


Figure 18. Traffic Dispersion on Peak Hour for Largest Airspace

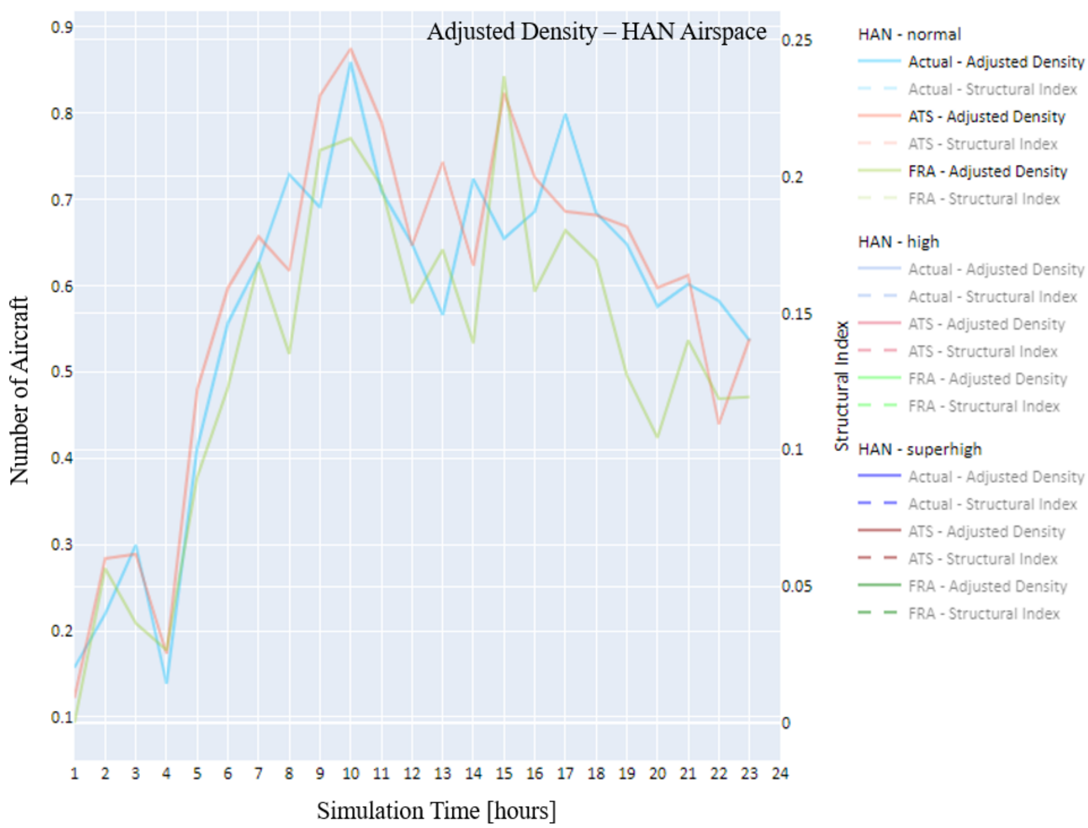


Figure 19. Adjusted Density HAN - Normal Demand

Figure 20. Comparison of Adjusted Density on Super High Demand for HAN and MUAC Airspace Areas

number of conflicts.

In order to check this correlation, a statistical test, such as Pearson Correlation Test is computed. For all scenarios the Pearson coefficient is bigger than 0.79 with a p-value < 0.05, which means that the two variables are highly correlated. Moreover, positive values indicate that the relationship between the variables is positive. This means that as the number of aircraft in the airspace increases, the likelihood of proximate pairs also increases. According to Figure 21, it can be seen that as the number of aircraft increases, the potential conflicts that may occur increase as well. Even when the number of aircraft passing through the airspace is similar, the number of conflicts can still vary significantly depending on the airspace structure scenario used.

Furthermore, the number of conflicts within the airspace influence the air traffic controller workload. Therefore, for a better illustration of this relation the workload index is computed as described in section IV. The methodology used incorporates the Solution-Space Diagram and enhances it by adding a third dimension through the severity score of the traffic situation.

The workload index is divided into four categories based on the score. Green category is characterised by traffic that doesn't affect the controlled aircraft's trajectory within the next 10 minutes.Yellow category has flights nearby the controller aircraft that could influence a potential conflict if the aircraft's trajectory changes. Orange category includes traffic close enough that the air traffic controller must consider it when managing the aircraft. Red category captures the critical traffic which requires immediate attention. In addition to these categories, there is an additional variable that gives penalty to the controller if there is a loss of separation. Although this situation excludes further action by the controller, it remains highly complex and unsafe, significantly increasing the psychological workload.

According to Figure 22, the overall penalty values decrease when the size of the airspace increases. Additionally, between choosing ATS Routes and FRA, the bigger the airspace area gets, the better option FRA is. This statement is sustained by the workload coefficient of the red category. As it can be seen in

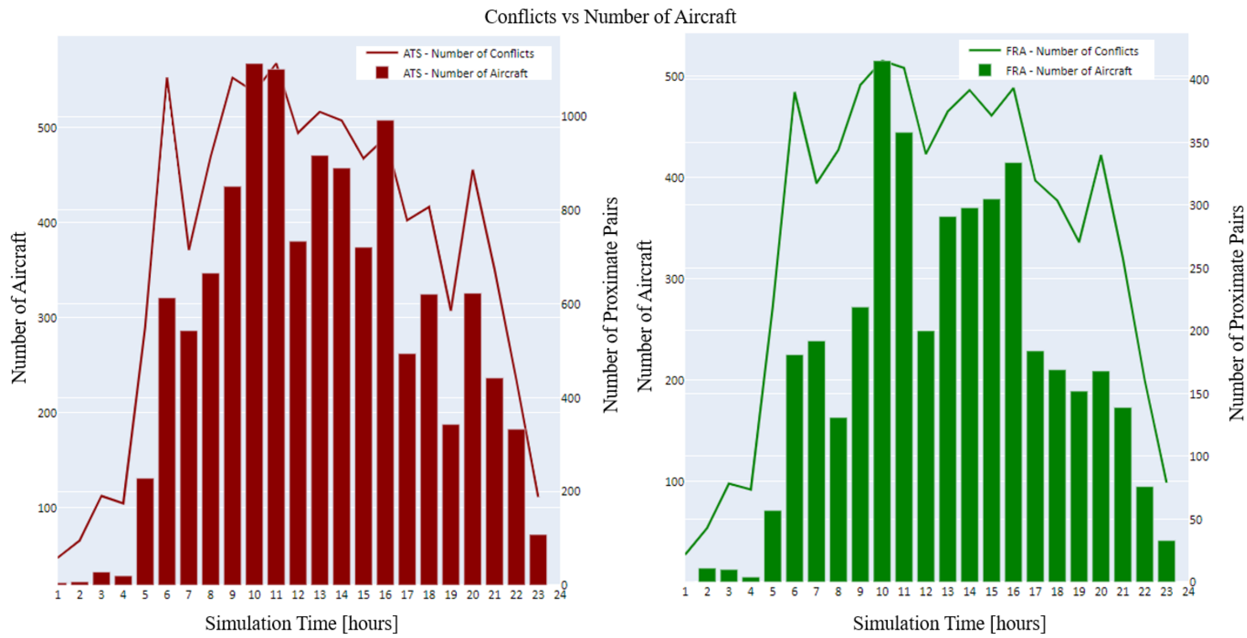


Figure 21. Conflicts vs Number of Aircraft HAN - Super High Demand

Figure 54, in the smallest airspace with super high demand, the workload of the controller is increased for all three operational environments. However, for a bigger airspace, the values consistently decrease. FRA scenario makes a big difference in case of CSE, which is the largest airspace. This means that the workload of the air traffic controller decreases once the airspace gets bigger, in terms of free routing, and remains almost constant in ATS routing.

In addition to the full Solution-Space Diagram workload estimation, a simplified version is computed as well. This simplified metric is based on [37] and it only considers the unsafe options of changing the heading of the controlled aircraft with respect to the difference in altitude of the observed aircraft. To illustrate an example of both techniques, it is considered an aircraft flying the airspace at 09:00. The callsign of the aircraft is *EQG2596*. The visual representation of the options that the ATCO can give to the controlled aircraft is presented in Figure 45. For the simplified version of SSD, Figure 49 presents the options of the aircraft that can have while maintaining the actual speed. In both pictures, there are six observed aircraft. More than that, three of the aircraft are green, one is yellow, one is orange, and one is red. As can be seen in this example, the controlled aircraft has a loss of separation with one of the observed aircraft, the red category.

In addition to this, let's consider an aircraft flying all operational modes in MUAC airspace in an high demand scenario. The callsign of the aircraft this time is *TOM2947*. The actual scenario of the traffic situation is presented in Figure 53a. In this diagram, six aircraft can be observed, one of the aircraft being in the red zone around the controlled aircraft. However, if the operational environment changes, the number of aircraft present on *TOM2947* increases to 11 aircraft as shown in Figure 53b. Moreover, in this scenario, there are two aircraft in red zone. If the operational environment changes to FRA, then the observed aircraft are different. As it can been seen in Figure 53c, there is no observed aircraft from the red category. Out of nine aircraft present on the diagram, more than 50% are on the green zone, which concludes that the workload of the air traffic controller is lighter in this individual case compared to the other two airspace structures.

The difference between the two representations is in the amount of options that the air traffic controller can offer to the controlled aircraft. Based on these options, the workload index changes as well, by

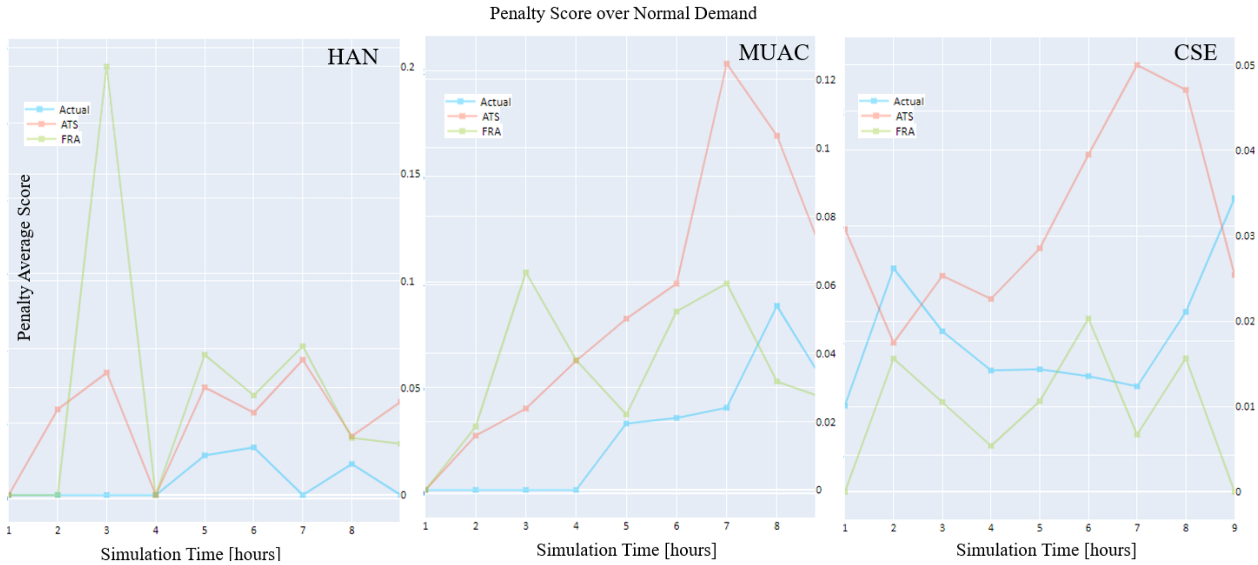


Figure 22. Penalty Score for normal demand for the first 9 hours of simulation

having bigger values for the simplified version, noted in this study by HD. Table 9 offers an overview of the values for both SSD and HD for the scenario mentioned above.

Table 9. Percentage of Unsafe Area - TOM2947 at 09:00

Category	Scenario	Total Value SSD	Total Value HD
Green	Actual	6.56	5.87
Yellow	Actual	26.2	27.98
Orange	Actual	26.19	29.68
Red	Actual	3.18	4.45
Green	ATS	4.04	4.04
Yellow	ATS	10.22	14.46
Orange	ATS	17.91	16.68
Red	ATS	2.91	3.4
Green	FRA	15.45	20.39
Yellow	FRA	11.06	12.86
Orange	FRA	48.79	59.8
Red	FRA	0	0

Generally, the bigger values of the workload index means that the air traffic controller has less options to give to the aircraft. This leads to a higher workload. If the categories are compared across different operational environments, then it can be noticed that while the green zone increases under FRA, the red zone decreases, having actually value 0. This example shows, that in this particular case, free routing is better than fixed routing or mixed routing.

But this scenario represents an individual case of one controlled aircraft. If the workload index is extended to the global level, it can be estimated an overall workload attributed to the controller. Figure 23 illustrates the global workload index for the red category, since the red one is the most critical one. The picture shows that as the size of the airspace increases, the workload index for FRA remains stable. In contrast, the workload index for the ATS Routes Network scenario increases significantly.

D. Airspace Structure

To capture the behavior of the traffic and the pattern of the airspace structure, the fractal dimension is computed. In this study five different grid sizes are considered. The ranges of the scales for each airspace area are presented in Table 10. For each scale, the new grid is computed over the airspace. The representation of the grids computed for MUAC airspace are shown in Appendix subsubsection A.I.1.

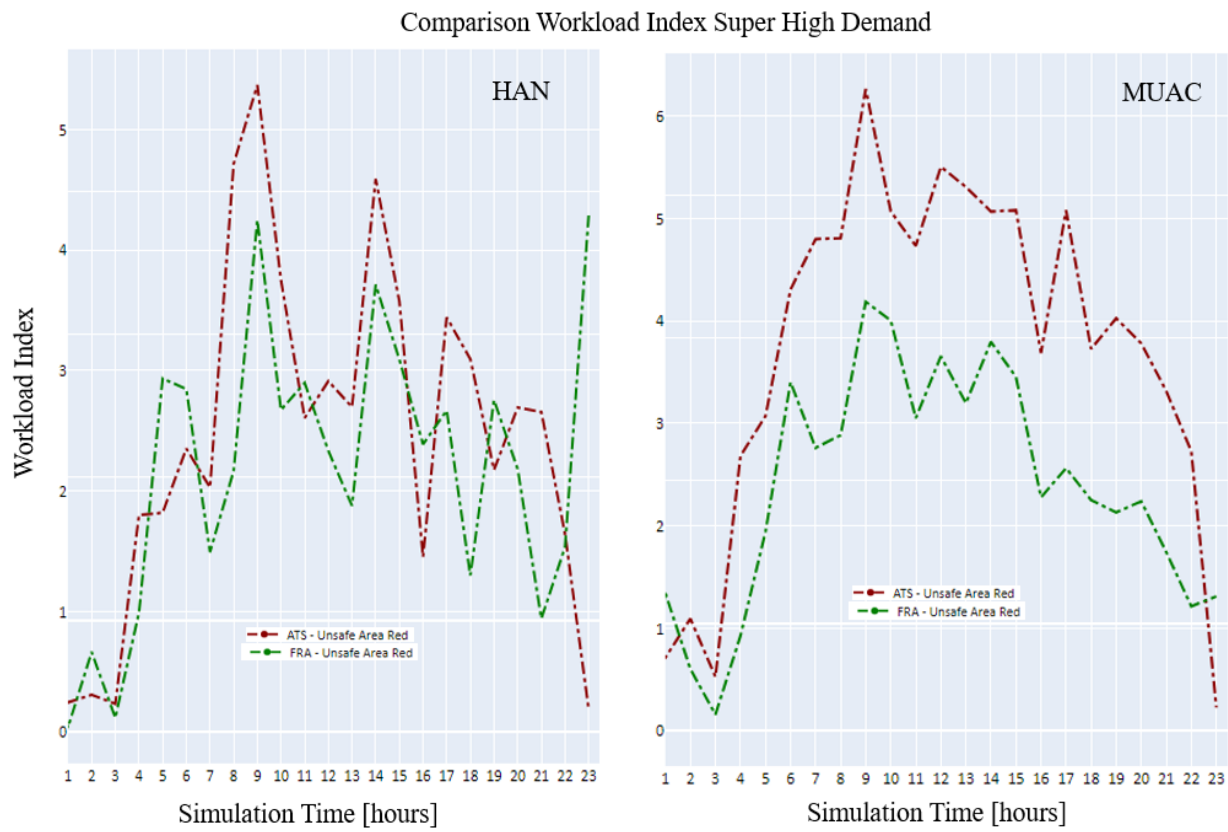


Figure 23. Comparison Workload Index on Super High Demand

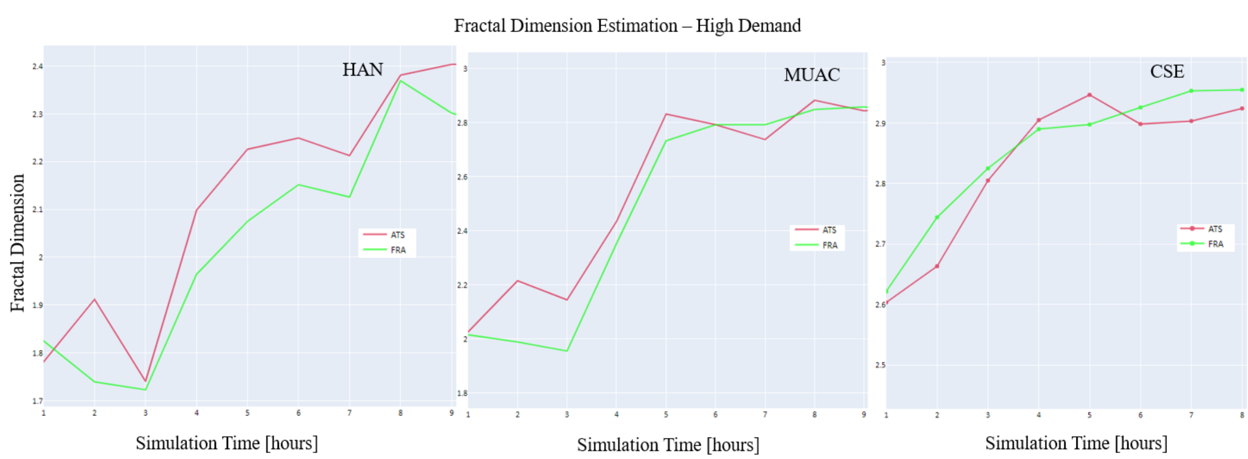


Figure 24. Comparison of Fractal Dimension on High Demand

Table 10. Scale Ranges Fractal Dimension

Airspace Area	Scale Range [NM]
HAN	[32 - 128]
MUAC	[64 - 256]
CSE	[256 - 1024]

The overall fractal dimension, calculated based on the provided scales, demonstrates that regardless of the airspace structure considered, all three scenarios exhibit a similar trend. Illustrated in Figure 24, across all sectors, ATS Routes Network consistently presents a higher fractal dimension compared to FRA. This indicates that the structured and fixed nature of ATS routes leads to greater complexity in air traffic management. These findings are further supported by the traffic mixture variable, which indicates that the traffic phase is moderate, with aircraft operating at varying altitudes, as described in Figure 17. Additionally, the dynamic density analysis reveals that the traffic distribution is non-uniform and dispersed throughout the airspace, leading to frequent changes in direction. However, the results indicate that the Free Route Airspace does not significantly alter the behavior of aircraft in flight, as the overall trend remains consistent across different scenarios.

E. Environmental Impact

Table 11. CO2 Emissions Index per Airspace Expressed in Tonnes

Airspace Area	[Actual ATS FRA]
HAN (Normal)	[5913 5867 2563]
HAN (High)	[6563 6559 2924]
HAN (Super High)	[11218 11411 5578]
MUAC (Normal)	[25537 255075 13561]
MUAC (High)	[28432 28399 15446]
MUAC (Super High)	[49425 49412 29205]
CSE (Normal)	[200059 200842 175263]
CSE (High)	[220944 221343 193996]
CSE (Super High)	[359727 359092 319967]

Based on Equation 21, the total CO_2 emissions are presented in Table 11. In general, it is known that FRA reduces the total distance flown by allowing the aircraft to follow a more direct route. This leads to lower fuel consumption and, consequently, means lower CO_2 emissions. As shown in Table 11, the values of CO_2 emissions of FRA compared with the others operational environments are reasonably smaller. For smaller airspace areas, the CO_2 emissions figures for FRA scenario are approximately half of those reported for the other operational environments.

All the complexity scores regarding all the complexity metrics discussed in this study, are summarized in Appendix in subsection A.M. In addition to these scores, the overall results of the indicators that contribute to the metrics are shown in this subsection of Appendix.

VII. Discussion

The simulation model computed on different airspace sizes and demands, offers several insightful observations regarding the efficiency and complexity of air traffic management within the FRA or ATS Routes Network regimes. The focus of discussion lies into the FRA and how this operational environment may accommodate future air traffic growth projections. Based on this discussion, the hypotheses mentioned in section V will be validated or not.

H1: The airspace usage under FRA is more extended than under the network of ATS routes. Overall, FRA offers significant advantages in optimizing airspace usage, as supported by the traffic behavior observed in the results. For example, according to section VI, the mixture of traffic is moderate, having an increased number of aircraft, which are descending or climbing. Figure 16 displays that vertical movements within the smallest airspace area, HAN, are relatively high, by indicating a substantial level of vertical dynamism.

Additionally, in the FRA scenario, this behavior of traffic is more pronounced. This can be explained by the flexibility attributed to airlines in planning their routes, allowing aircraft to exit the airspace earlier compared to the flights which follow the traditional ATS routes. This leads to create more space in the en-route airspace. This aspect is enhanced even during the trajectories builder process, where the number of computed FRA flights decreases once the trajectories are built. While this indicates a potential solution for reducing congestion in the en-route environment, it is important to state that this alone is insufficient. Shifting the flights from en-route environment, may lead to congestion in other areas, such as the approach or tower control areas.

Going deeper into the results, it can be seen that despite the vertical movements, which offers bigger complexity within the airspace, the FRA scenario presents a smaller overall complexity score. This is presented in Table 6, Table 7, and Table 8. This apparent contradiction can be described by the traffic distribution across the space. By looking into the traffic distributions, FRA facilitates a more even distribution of traffic across the airspace, leading to a lower density in particular areas. Therefore, this confirms the first hypothesis of this study which concludes that overall the FRA environment is maximizing the airspace usage.

H2: The level of air traffic controller workload increases due to the creation of invisible hot spots on the map under the FRA operational environment.

An important aspect of complexity is the assessment of the air traffic controller workload. In this study, this aspect is expressed by estimating the number of conflicts and also by the range of options that the controller can offer to the aircraft which is being controlled. In literature is studied, that the greater the number of conflicts, the higher the indicated workload for the controller. Therefore, the number of conflict in different scenarios is computed. At the beginning, by using Pearson Correlation Test, it is shown that there is a positive link between number of conflicts and number of aircraft. Thus, the larger number of aircraft in the airspace, the bigger the number of conflicts. If each scenario is considered, it is noticed that the number of conflicts within the FRA is smaller than the number of conflicts in ATS. And this happens despite the type of demand or the size of the airspace area. An example of super high demand across all relevant airspace areas is illustrated in Figure 66.

However, if the number of aircraft are displayed for each type of airspace structure, as can be seen in Figure 63, the difference in number of aircraft is exponentially bigger between ATS environment and FRA environment. However, the difference in numbers of conflicts between these two environments is not that significant. Hence, it can be concluded that the freedom of choosing the flight path can lead to a potential increase in workload of the controller, limiting the airspace to a smaller capacity. In addition to this, the freedom of choosing the routes affects the operational environment by creating ”invisible intersection points” which might generates a higher workload level.

Looking at the workload index, it is clear that ATS routing results in a higher workload because traffic tends to concentrate more at route intersections than in FRA. Although ATS routes lead to increased workload and complexity, it’s important to note that a similar number of conflicts occur in the airspace despite the significant difference in the number of aircraft between the two environments. This suggests that air traffic controllers face nearly the same number of conflicts while managing fewer aircraft under the FRA system, which compromises airspace capacity. Therefore, the second hypothesis is validated.

H3: Managing high demands of free routes in a larger airspace area significantly increases its complexity.

When the size of the airspace is considered, it can be noted that the index for the workload decreases once the airspace area is getting bigger under FRA operations. In the case of ATS scenarios, this index remains constant. Basically, this means that in larger airspace areas FRA is more useful to accommodate high demands of traffic. This affirmation can be supported by analysing the penalty score. According to Figure 22, the overall penalty values decrease when the size of the airspace increases and this is true for both operational environments. In summary, the third hypothesis is validated for ATS routing, as its complexity increases with larger airspace areas. However, this hypothesis is not validated for FRA, where even under super high demand, the complexity decreases as the airspace expands. This demonstrates that FRA handles larger airspace areas more efficiently than ATS routing.

H4: Due to free flight, the number of flight interactions is smaller in the FRA environment than in the ATS Routes Network environment.
If complexity is assessed through the hours of flight interactions, then in general the ATS Routes environment is more complex. This is because all the changes in flight that aircraft should follow on fixed routes. However, study shows that in small airspace areas, if the demand increases, the complexity of handling aircraft in a FRA is getting higher. The significant spikes in interactions around 09:00 and 12:00 in the FRA scenario highlight the increased complexity during peak times. Therefore, a smaller overall complexity score within FRA with a bigger complexity assessment during peak hours explains the nature of freely choosing the flight paths. The congestion within the airspace in FRA during peaks is due to the fact that the number of routes that the aircraft are flying increases considerably. Therefore, the fourth hypothesis is partially true, because in general the ATS Route Network presents higher level of complexity with respect to the flight interactions, but when the demand is getting higher and the airspace area remains small, the airspace becomes more complex in the FRA environment.

H5: An airspace operating under ATS routes structures has a smaller complexity compared to an airspace operating under FRA.
The fractal dimension, which measures complexity in air traffic patterns, is consistently higher for ATS Routes Network compared to FRA. This indicates that the structured and fixed nature of ATS routes leads to greater complexity in air traffic management. However, there is not a big difference in estimating the value of fractal dimensions, because in all cases the traffic is very diverse and full of dynamism. The fractal dimension approaches a value of nearly 3 in all scenarios, because the flights are dispersed in all directions. This finding contradicts the fifth hypothesis. While FRA shows localized complexity, the overall complexity of ATS routing is more rigid and consistently higher across all analysed aspects.

H6: The footprint of CO_2 emissions for the FRA environment is smaller than the one for ATS Routes Network.
If the environmental impact is addressed, the significant reduction in CO_2 displayed in Table 11 highlights the efficiency of FRA in small areas due to the direct routes. However, an interesting observation can be made when comparing the scenarios across larger airspace regions. In this case, the figures of FRA still demonstrates lower CO_2 emissions, but the differences between the ATS Routes Network is less emphasised. This can be explained by the fact that on a larger airspace areas, the direct route may not coincide with the Great Circle Route. The Great Circle is the shortest path between two points on the surface of a sphere, such as the Earth. Therefore, the aircraft are flying more. Furthermore, the sixth hypothesis that the FRA environment should have a smaller impact on $CO_2 emissions$, is supported, especially in smaller airspace areas where the reduction in emissions is significant.

H7: The complexity score for FRA is consistently lower than that for the ATS Routes Network across all demand levels studied in this paper.
In the end, it is important to establish the overall impact of FRA compared to ATS Routes Network in the simulation model. For that, a comparison on the overall values for each complexity metric is calculated. Based on the independent variables, the overall values are displayed in Appendix in subsection A.M. The computation of the metrics for the actual scenarios are made to have them as reference. The logic of the complexity metrics is as follows: the bigger the value of the metric is, the more complex the airspace area is.

1. Small airspace area
Overall, the FRA environment is better than ATS Routes Network. On normal demand, compared to the actual scenario, FRA expresses a bigger value in workload, which means that the complexity of the airspace is higher when the aircraft are flying free routes under this condition. However, once the demand increases, the air traffic controller's capabilities in managing the workload within FRA are getting better than in the actual scenarios. Table 12 shows

how the complexity metrics compare between FRA and ATS routes, indicating whether FRA performs better or worse than ATS. A negative value means that FRA environment performs better than ATS routes scenario. Same principle can be found in Table 15 where it is shown the comparison of FRA and ATS scenarios with the actual operating mode. Despite the fact that FRA environment is better for all types of demands, according to Table 12 and Table 15, it can be seen that performance of FRA in dynamic density slightly decreases once the traffic demand is getting bigger. For example, compared to ATS scenarios, in super high demand, the performance of this metric increases with 42.54%, while on the normal demand, a performance of almost 79.55% is registered. Compared to the actual scenarios, the traditional fixed routing presents better and worse values compared to the actual scenarios. On the normal demand, the complexity is higher, but the environmental impact is smaller. Once the demand increases, the fractal dimension and the dynamic density presents positive values for ATS routes.

Table 12. Percentage Increase Compared with ATS Scenarios - HAN

	Normal	**High**	**Super High**
Metric*	**FRA**	**FRA**	**FRA**
DD	-79.55	-71.88	-42.54
WI SSD	-17.33	-24.5	-15.14
WI HD	-20.76	-27.46	-17.91
FD	-3.96	-4.55	-2.63
CO2	-56.31	-55.42	-51.11

* *DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension*

2. Medium airspace area

In MUAC airspace, which is the medium airspace size in this study, FRA has the best performance among all three types of operational environments. Comparing with the ATS routes scenarios, it is less complex to manage air traffic under FRA. However, compared with the smallest airspace, there is a small improvement in the performance of FRA. For instance, let's consider the workload index. In small airspace area, FRA is better with approximately 15 - 18%, while in medium airspace, this percentage increases to 25 - 27%. This can be seen in Table 12 and Table 13. Contrary, comparing the flight interactions within actual scenarios and FRA on super high demands within these two size of airspace areas, it can be seen that the performance of FRA slightly decreases. The comparison can be seen in Table 16. If in the smallest airspace area, FRA performs with 43.49% better than actual scenarios, in MUAC airspace, the percentage is 22.77% in the favor of FRA.

Table 13. Percentage Increase Compared with ATS Scenarios - MUAC

	Normal	**High**	**Super High**
Metric*	**FRA**	**FRA**	**FRA**
DD	-51.55	-34.04	-24.84
WI SSD	-26.71	-27.36	-25.05
WI HD	-28.39	-29.00	-26.72
FD	-3.17	-2.26	-1.09
CO2	-46.83	-45.61	-40.90

* *DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension*

3. Large airspace area

In larger airspace areas, a significant increase in performance is the workload index of FRA. This index provides better performance compared with ATS routing according to Table 14. Compared to medium and small airspace areas, the workload complexity in the FRA regime is nearly half that of the other operational modes, including the ATS Routes Network and actual scenarios. Comparing Table 14 and Table 17, it can be seen that FRA handles the high demands in traffic better than the ATS routes or the combination of direct routes and fixed ones.

Table 14. Percentage Increase Compared with ATS Scenarios - CSE

	Normal	High	Super High
Metric*	FRA	FRA	FRA
DD	-60.49	-36.46	-23.81
WI SSD	-51.79	-51.82	-50.24
WI HD	-53.17	-53.76	-52.24
FD	-1.45	-1.07	-0.36
CO2	-12.74	-12.36	-10.9

* *DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension*

Therefore, by analysing the performances of all the metrics in different scenarios, it is easy to validate the last hypothesis.

VIII. Conclusion

To conclude this study, it can be affirmed that the implementation of FRA impacts the sector capacity in several ways when assessing different complexity metrics.

In general, the positive aspect of FRA is that this operational environment distributes traffic more evenly across the airspace, by maximizing the airspace usage. This leads to congestion reduction and reduction of the overall number of conflicts, especially in larger airspace areas. However, the implementation of free routing may increase the workload of the air traffic controllers due to the less predictable nature of flight paths. Moreover, it can shift the workload of the air traffic controllers towards the lower airspace, affecting the approach and tower control areas. Therefore, while FRA reduces the number of conflicts, this study shows that the reduction of conflicts does not reflect a big improvement, since the reduction of conflicts is not that prominent compared with the reduction of overall number of aircraft within the airspace. This introduces new challenges in conflict detection and resolution.

At the beginning of the study, few research questions are addressed. The results and subsequent discussion provide clear answers to these questions, demonstrating how the findings align with the initial objectives.

Research Question 1: How does the implementation of FRA impact sector capacity when assessed using different traffic complexity metrics?
Initially, the study shows that the airspace capacity is constraint by several factors. One of the aspects is the traffic distribution. It can be said that larger airspace areas tend to benefit more from FRA due to better traffic dispersion and more efficient use of available space for the high and super high demands. On the other side, the number and nature of flight interactions can significantly affect sector capacity. However, with FRA, the flight interactions can be reduced due to a lower number of required heading changes. Another important aspect is the air traffic controller workload. In the FRA scenario, under normal demand, the controller's workload increases due to the need of managing more dynamic and less predictable flight paths. However, under high demand, the air traffic controller's workload is handled more effectively in FRA compared to the ATS routing environment. The traffic density also plays an important role in determining sector capacity. Higher traffic densities can lead to increased complexity and workload, particularly in smaller airspace areas where the benefits of FRA are less noticeable.

Research Question 2: How does the implementation of FRA contribute to the sustainability of air transport? Given the EU's ambitious project to make Europe the first zero-emissions continent by 2050, the environmental aspect of air traffic management is important. Therefore, this study reveals that the implementation of FRA contributes to the sustainability of air transport by positively affecting various environmental factors. FRA generally leads to more direct routes, reducing flight distances and consequently lowering fuel consumption and CO_2 emissions. By allowing more direct flight paths, FRA reduces the overall fuel burn, contributing to both economic and environmental sustainability.

The contribution of FRA to sustainability in terms of reducing CO_2 emissions and fuel consumption is significant. However, the extent of its benefits can vary depending on the size of the airspace and

Table 15. Percentage Increase Compared with Actual Scenarios - HAN

	Normal	Normal	High	High	Super High	Super High
Metric*	**ATS**	**FRA**	**ATS**	**FRA**	**ATS**	**FRA**
DD	71.43	-64.94	39.11	-60.89	-1.66	-43.49
WI SSD	28.66	6.37	29.57	-2.17	9.47	-7.1
WI HD	31.11	3.89	30.57	-5.28	9.69	-9.95
FD	0.5	-3.48	0.46	-4.11	-1.3	-3.9
CO2	-0.78	-56.64	-0.05	-55.44	1.72	-50.27

** DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension*

Table 16. Percentage Increase Compared with Actual Scenarios - MUAC

	Normal	Normal	High	High	Super High	Super High
Metric*	**ATS**	**FRA**	**ATS**	**FRA**	**ATS**	**FRA**
DD	10.46	-46.49	10.39	-27.19	2.75	-22.77
WI SSD	32.54	-2.87	19.71	-13.04	13.07	-15.25
WI HD	32.48	-5.13	17.86	-16.33	11.54	-18.27
FD	0.4	-2.79	-0.75	-2.99	-1.08	-2.16
CO2	-0.12	-46.9	-0.12	-45.67	-0.03	-40.91

** DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension*

Table 17. Percentage Increase Compared with Actual Scenarios - CSE

	Normal	Normal	High	High	Super High	Super High
Metric*	**ATS**	**FRA**	**ATS**	**FRA**	**ATS**	**FRA**
DD	16.92	-53.8	6.94	-32.05	6.38	-18.95
WI SSD	8.74	-47.57	7.84	-48.04	4.52	-47.99
WI HD	9.09	-48.92	8.14	-50	4.92	-49.89
FD	-0.36	-1.81	-0.71	-1.77	-1.06	-1.41
CO2	0.39	-12.39	0.18	-12.2	-0.18	-11.05

** DD = Dynamic Density, WI = Workload Index, FD = Fractal Dimension* the specific traffic conditions. While FRA is highly effective in larger airspace areas, its impact may be less obvious in smaller areas where the complexity and workload for controllers can increase during peak traffic periods.

Concluding, this study shows that FRA is an excellent option for larger airspace areas due to its ability to effectively distribute flights across the airspace. This distribution helps with managing high traffic demands, reduces congestion, and enhances both economic and environmental sustainability.

A. Limitations

There are several limitations to this study that should be taken into account when analyzing the findings and conclusions. First of all, the analysis was carried out without access to the most recent data, which made it difficult to represent the most recent dynamics and trends in air traffic. The analysis of route evolution and its effects on airspace capacity and complexity was limited due to the lack of historical data for the routes. Another limitation was the computer's performance, which limited the amount of larger or more detailed simulations that could be completed. In conclusion, the study's findings may have been less accurate and robust as a result of these limitations.

B. Recommendations for Future Work

Further studies should focus on several areas to build upon the outcomes of this study and enhance the understanding and management of airspace capacity and complexity. One direction can be the financial assessment on airlines flying on Free Route. Due to the different prices that countries have in Europe, some airlines prefer to take a longer path rather than fly in FRA. This direction and study can estimate the influence of adoption of FRA within Single European Sky, SES context.

Another direction that can be explored is to evaluate the dynamic sectorisation within airspace capacity. The objective is to check the dynamic sectorisation in optimizing the airspace management. Based on this analysis, some strategies can be formulated to improve the air traffic flow and to reduce the number of delays. In addition to this, it can be beneficial if there will be studies based on the implementation of FRA within the approach or tower environment. The increase of demand does not occur just on the en-route environment, so the implementation of FRA on such sectors may be a good strategy.

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Appendix

Table of Contents

A. Appendix A

A. Traffic Demand Trends

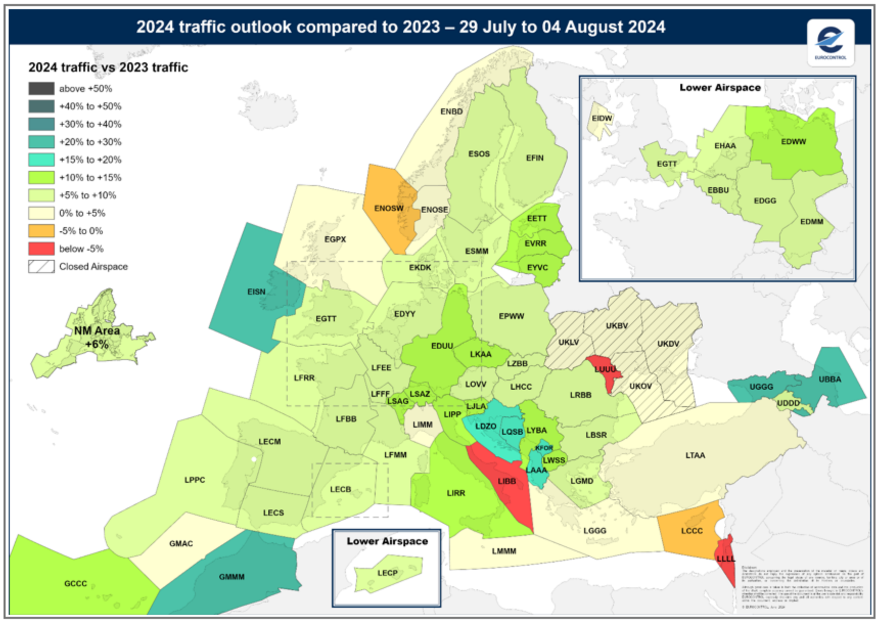


Figure 25. 2024 Traffic Outlook Compare to 2023 - 29 July to 4 August 2024
[38]

B. Airspace Definition

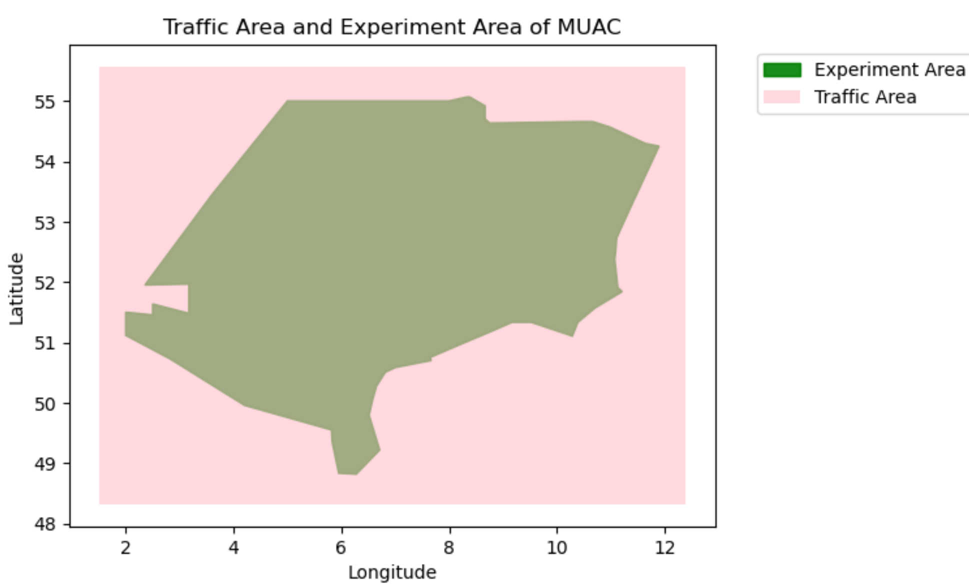


Figure 26. Defining Experiment and Traffic Areas

C. Mesh Computation

1. About Mesh
As mention in subsubsection IV.C.2, some of the indicators from the complexity model are evaluated using a mesh. The process consists of dividing the airspace into 4D uniform cells, collecting data within each cell, and subsequently using this data to compute the sector-level indicators. A representation of a mesh is shown in Figure 27.

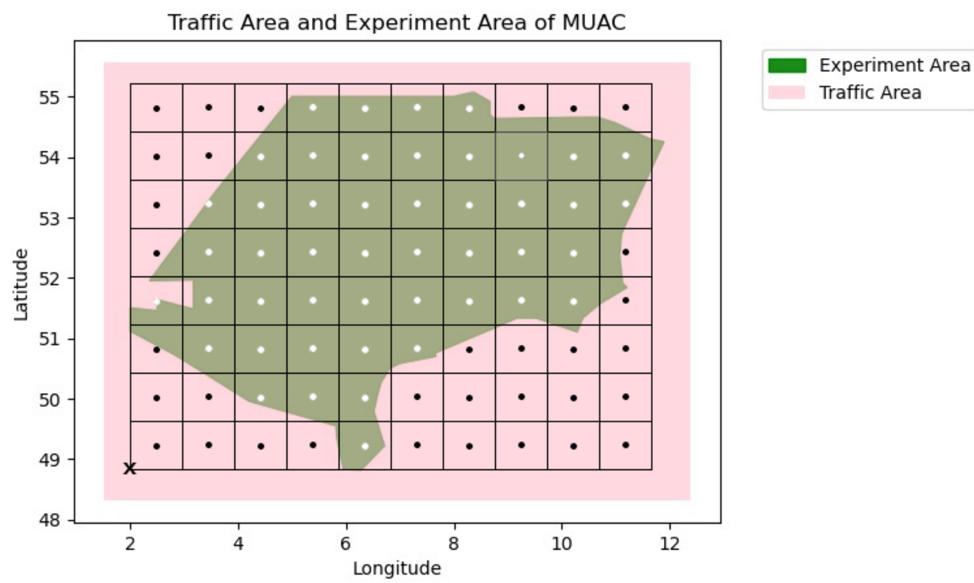


Figure 27. Horizontal view of MUAC airspace tiled by the mesh

In order to start building the mesh, the minimum latitude and minimum longitude were calculated. In the figure above, this is represented by the 'X' symbol and it shows the start point from where the mesh will be computed. Each cell has four parameters, three spatial and one temporal. In this study, it is considered that a horizontal representation of the cell is defined by a square. Therefore, as can be seen in the representation above, the cell has the latitude dimension equal with the longitude one. While the cell size is defined in degrees, the height of it is expressed in feet. In a 3D environment, the mesh of airspace is represented in Figure 28. Since the airspace is not a regular shape, it is important to determine in which cells the calculations are performed. In order to do that, the center of each is cell is estimated and if its coordinates lie inside the airspace's boundaries, then the cell has the status 'active'. In Figure 26, the squares with the white circles represent the active cells where the calculations are computed.

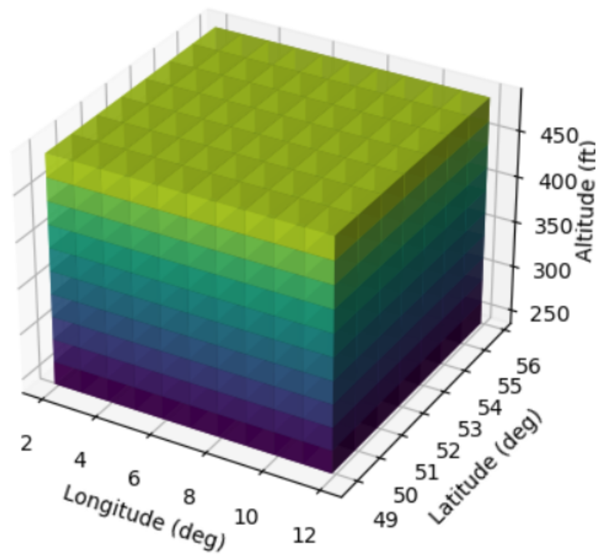
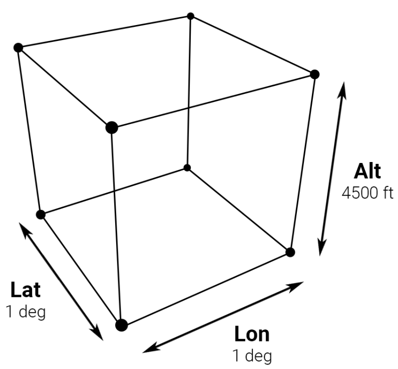
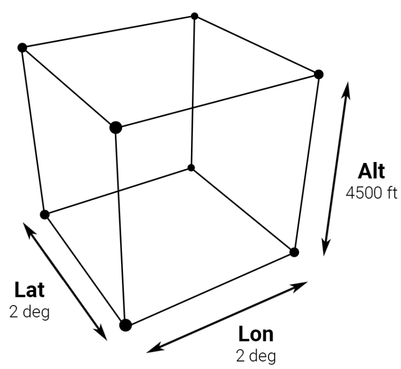


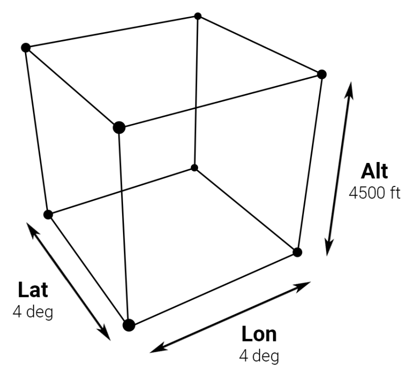
Figure 28. 3D Mesh Representation



(a) Cell parameters for HAN airspace



(b) Cell parameters for MUAC airspace



(c) Cell parameters for CSE airspace

Figure 29. Cell Dimension Airspace (LATxLONxALT)

Figure 29 shows the cell parameters that are taking into the simulation model for each airspace. In this study, the fourth component, the temporal parameter, is considered to be 60 minutes and during all the scenario computations this values does not change. To prevent boundary effects, a spatial displacement of the mesh is applied. The spatial displacement is computed as follows.

1) Horizontal Perspective:
   - The starting point for creating the mesh is adjusted horizontally by a value of $\frac{\text{cell}_{\text{size}}}{2}$.
   - This shift is applied to both latitude and longitude.
2) Vertical Perspective:
   - When the shift is required in altitude, an additional 1000 ft is added to the starting altitude point.

2. Mesh Offsets

Table 18. Mesh Offsets - Dynamic Density

Airspace Name	Complexity Metric	Offsets [deg]
HAN	Dynamic Density	(0.5,0,0), (0,0.5,0), (0.5,0.5,0)
MUAC	Dynamic Density	(1,0,0), (0,1,0), (1,1,0)
CSE	Dynamic Density	(2,0,0), (0,2,0), (2,2,0)

Table 19. Mesh Offsets - Fractal Dimension

Airspace Name	Size of box	Offsets [deg]
HAN	0.533	(0.266,0,0), (0,0.266,0), (0,0,1000), (0.266,0,1000), (0,0.266,1000)
HAN	0.75	(0.375,0,0), (0,0.375,0), (0,0,1000), (0.375,0,1000), (0,0.375,1000)
HAN	1.066	(0.533,0,0), (0,0.533,0), (0,0,1000), (0.533,0,1000), (0,0.533,1000)
HAN	1.516	(0.758,0,0), (0,0.758,0), (0,0,1000), (0.758,0,1000), (0,0.758,1000)
HAN	2.133	(1.067,0,0), (0,1.067,0), (0,0,1000), (1.067,0,1000), (0,1.067,1000)
MUAC	1.066	(0.533,0,0), (0,0.533,0), (0,0,1000), (0.533,0,1000), (0,0.533,1000)
MUAC	1.516	(0.758,0,0), (0,0.758,0), (0,0,1000), (0.758,0,1000), (0,0.758,1000)
MUAC	2.133	(1.067,0,0), (0,1.067,0), (0,0,1000), (1.067,0,1000), (0,1.067,1000)
MUAC	3.016	(1.508,0,0), (0,1.508,0), (0,0,1000), (1.508,0,1000), (0,1.508,1000)
MUAC	4.266	(2.133,0,0), (0,2.133,0), (0,0,1000), (2.133,0,1000), (0,2.133,1000)
CSE	4.266	(2.133,0,0), (0,2.133,0), (0,0,1000), (2.133,0,1000), (0,2.133,1000)
CSE	6.033	(3.017,0,0), (0,3.017,0), (0,0,1000), (3.017,0,1000), (0,3.017,1000)
CSE	8.533	(4.267,0,0), (0,4.267,0), (0,0,1000), (4.267,0,1000), (0,4.267,1000)
CSE	12.066	(6.033,0,0), (0,6.033,0), (0,0,1000), (6.033,0,1000), (0,6.033,1000)
CSE	17.066	(8.533,0,0), (0,8.533,0), (0,0,1000), (8.533,0,1000), (0,8.533,1000)

D. Data Sources

Initially, the dataset integrated in the simulation model needs to be validated. To check if the volume of data is representative of the expected traffic demand and flow, the boxplot method is applied for three random days from the month June, 2018. Based on the results shown in Figure 30, the traffic samples for three days did not show any outlier values which could introduce bias in the data. The traffic volume is approximately the same in all days. The figure also shows the mean number of flights per hour (black diamonds) and the standard deviation (black lines extending above and below the black diamonds). In addition to this, it is also needed to check the representative patterns in terms of traffic distribution throughout a day. In order to accomplish this, Kolmogorov-Smirnov test is used which determines if two datasets differ significantly. The hypothesis of the test are:

- **Null Hypothesis H0:** The two samples come from the same distribution. There is no statistically significant difference between the two distributions.
- **Alternative Hypothesis H1:** The two samples come from different distributions. There is a statistically significant difference between the two distributions.

The results shows that the KS statistic is approximately 0.2083, indicating that there is a maximum difference of about 20.83% between the cumulative distribution functions of the datasets at some point. The p-value is approximately 0.686 which is > 0.05, which means that there is no evidence to reject the H0. The conclusion is that the samples follow similar pattern. So, any date among these three can be chosen. Therefore, Wednesday, 6th of June 2018 was chosen.

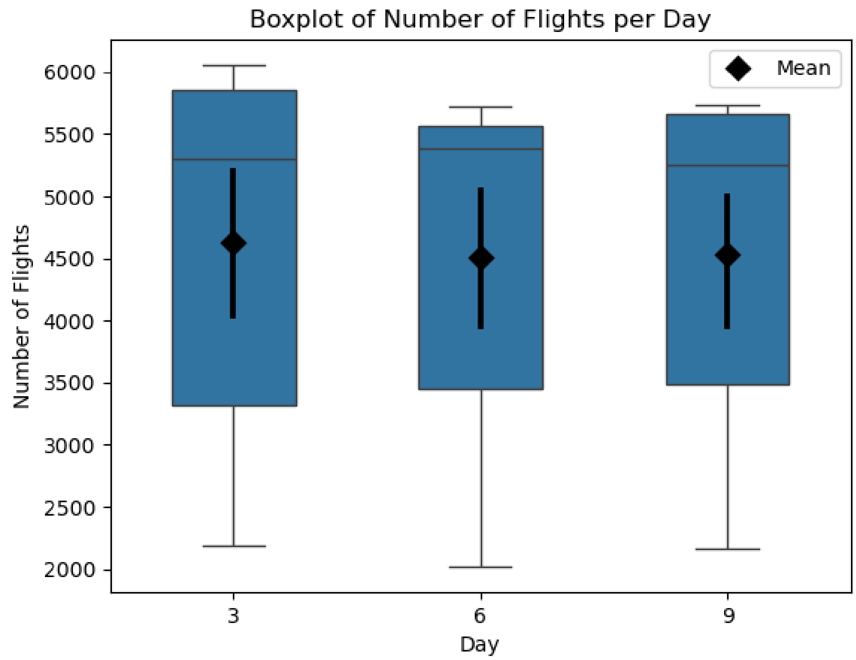


Figure 30. Validation Data - Boxplot Method

Table 20. Airspace Data Variables

Variable Code	Variable Name	Description
Sect_grp	Sector Group Name	The name of the airspace of interest
LAT	Latitude	Latitude in decimal degrees
LON	Longitude	Longitude in decimal degrees

Table 21. Traffic Data Variables

Variable Code	Variable Name	Description
ECTRL_ID	ECTRL ID	Unique numeric identifier for each flight in Eurocontrol database
Callsign_id	Aircraft Callsign	Unique code identifier for each flight. The callsign is computed by AC Operator + Last 3 digits from ECTRL ID. Example: ECTRL ID:218860705, AC Operator:KLM. Callsign = KLM705
Seq_nr	Sequence Number	Numeric sequence number of the points crossed by the flight in chronological order
Time_over	Time Over	Time (UTC) at which the point was crossed
Flight_Level	Flight Level	Altitude in flight levels at which the point was crossed
LAT	Latitude	Latitude in decimal degrees
LON	Longitude	Longitude in decimal degrees
WPT	Waypoint	The name of the point that is flying over. It is generated by Callsign + Sequence Number
ADEP	Airport Departure	ICAO airport code for the departure airport of the flight
ADES	Airport Arrival	ICAO airport code for the destination airport of the flight
AC_Type	Aircraft Type	The ICAO aircraft type designator is a two-, three- or four-character alphanumeric code designating every aircraft type that may appear in flight planning

E. Scenario Example

This section presents a small example of how a scenario of .scn format is made.

```
# These are the flights of 2018-06-06 (Source: EUROCONTROL)
# Structure: Actual, Airspace: HAN, Demand: normal, Day type: Weekday
00:00:00.00> PLUGIN COMPLEXITY
00:00:00.00> AIRSPACE HAN 24000 47000
00:00:00.00> COCA 1 4500 3600 0 0 0
00:00:00.00> WLSSD ON 600 0 86400
00:00:00.00> FD 5 ON 300 0 86400
00:00:00.00> ASAS ON
00:00:00.00> FF

# Computing the trajectories
00:00:00.00> CRE FDX2362, B77L, 38.4675, 108.95306, 301.0462798986953, 32000, 300
00:00:00.00> ADDWPT FDX2362, 39.36917, 106.97917, 32000
00:00:00.00> ADDWPT FDX2362, 39.79917, 105.99222
00:00:00.00> ADDWPT FDX2362, 40.21556, 105.00528
00:00:00.00> ADDWPT FDX2362, 40.61861, 104.01833
00:00:00.00> ADDWPT FDX2362, 41.00861, 103.03139
00:00:00.00> ADDWPT FDX2362, 41.38583, 102.04445
00:00:00.00> ADDWPT FDX2362, 41.75028, 101.0575
```

Figure 31. Scenario File Example - Airspace: HAN, Airspace Structure: Actual Trajectories, Demand: Normal Demand

F. Aircraft Types

Table 22. Changes of Aircraft Types

Aircraft Type Old	Aircraft Type New
SUKHOI Superjet 100-95 (SU95)	SEmbraer E-Jet E170
Ilyushin Il-76 (IL76)	Airbus A400M
Tupolev Tu-204	Boeing 757
Ilyushin Il-96	Airbus A340

G. COCA Project

This appendix section is dedicated to the analysis of dynamic density via the COCA Project. All the results of this complexity metric can be accessed in the study repository: GitHub - Dynamic Density. Further in this appendix, MUAC airspace on a high demand is used to illustrate different models of the plots.

1. COCA Meshes

The meshes used for each airspace area for this complexity metric can be seen in the study repository: GitHub - Dynamic Density - Meshes. The graph displays the mesh used on different airspace areas including the spatial displacements used in the model. On the map, different colored cells can be found, such as black rectangular cells which mean the inactive cells and red rectangular cells which are dedicated for the cells which are active within the airspace. The activity status of the cell is determined by estimating whether its center is within the boundaries of the airspace. A representation of this plot is illustrated in Figure 32.

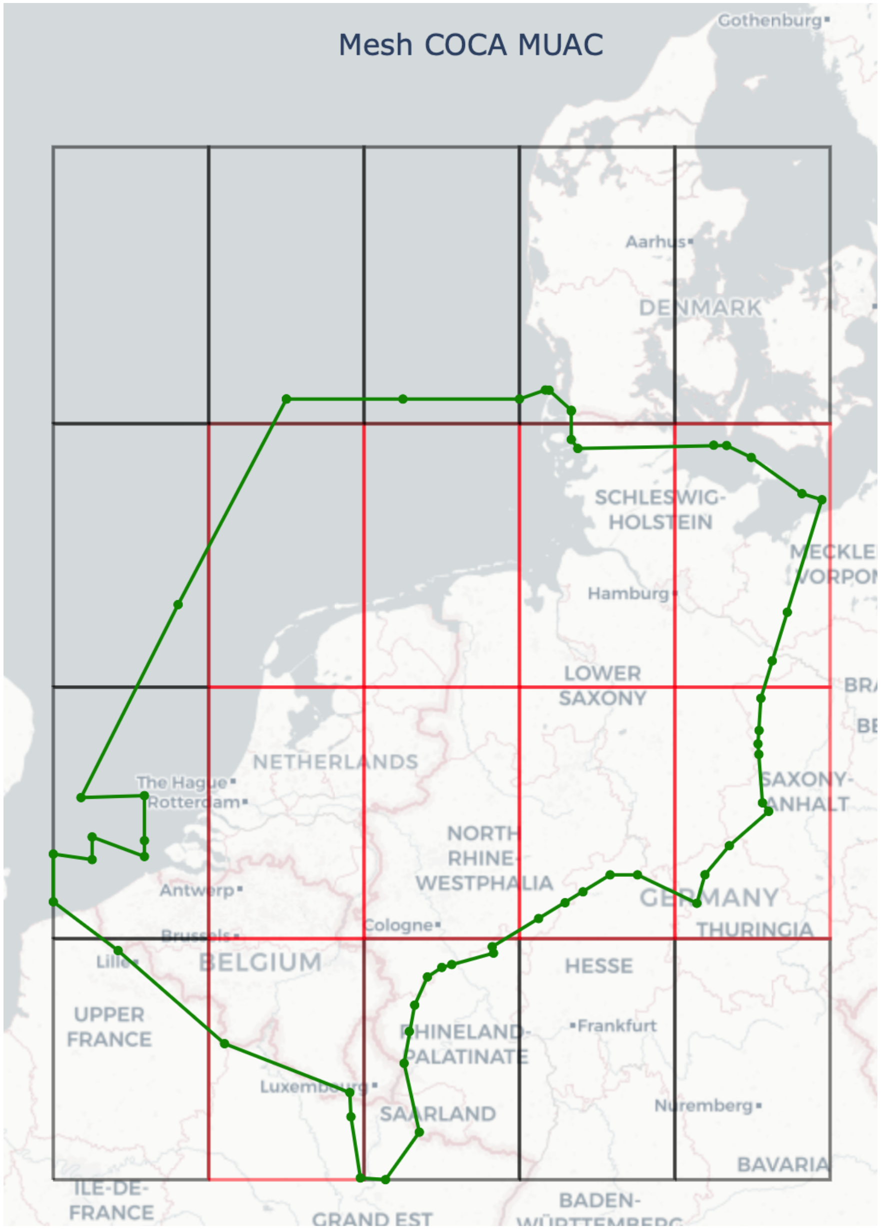
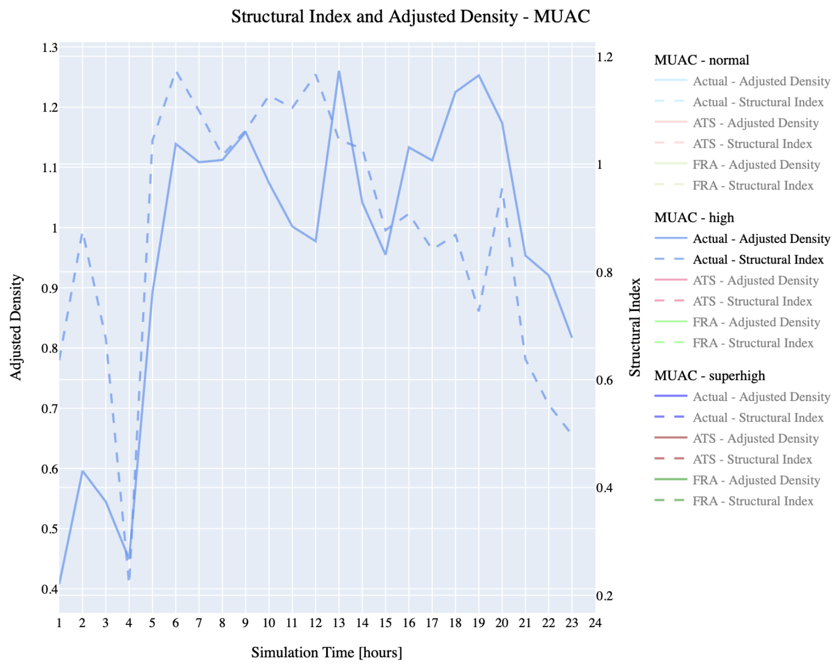


Figure 32. Mesh used for MUAC airspace

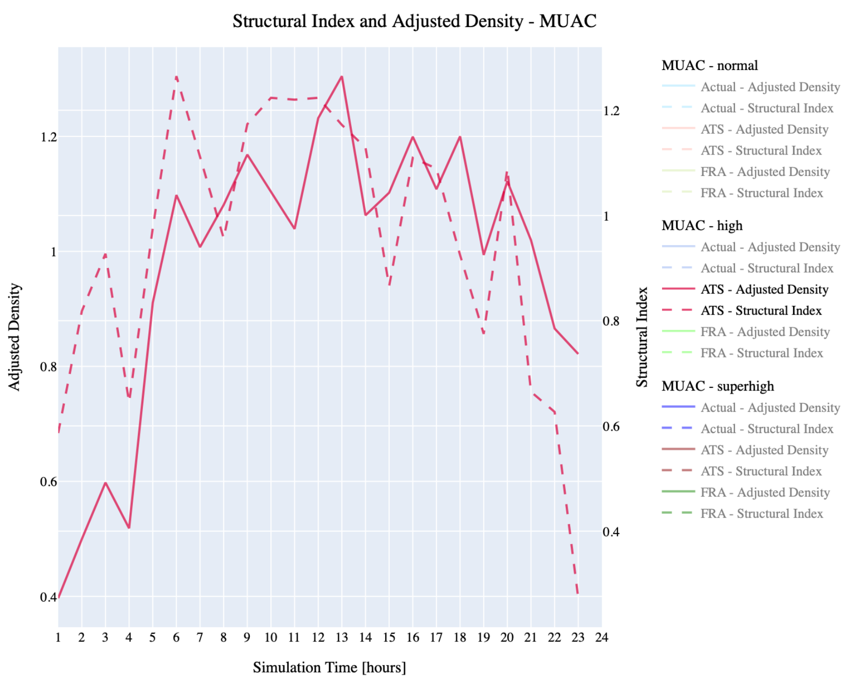
- In order to access the interactive map which contains the mesh for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Dynamic Density - Meshes - HAN.
- In order to access the interactive map which contains the mesh for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Dynamic Density - Meshes - MUAC.
- In order to access the interactive map which contains the mesh for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Dynamic Density - Meshes - CSE.

2. Adjusted Density and Structural Index

The plots resulted from the scenario simulations for all the airspace areas can be seen in the study repository: GitHub - Dynamic Density - AD and SI. Also, a model of this plot is shown in Figure 33.



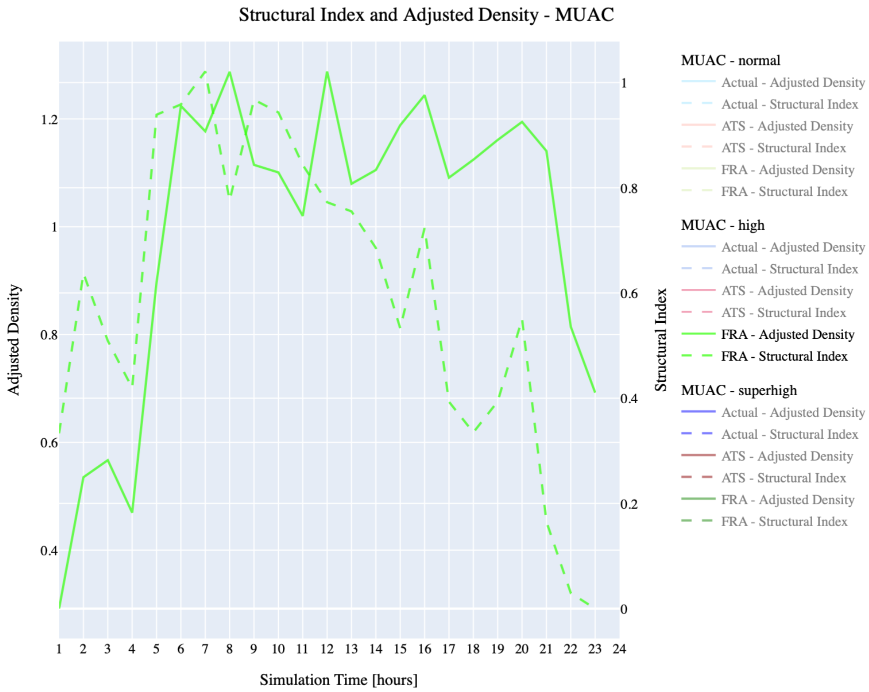
(a) Actual high demand



(b) ATS high demand

Figure 33. Adjusted Density and Structural Index - MUAC

- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Dynamic Density - AD and SI - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the



(c) FRA high demand

Figure 33. Adjusted Density and Structural Index - MUAC (cont.)

repository of this study: GitHub - Dynamic Density - AD and SI - MUAC.

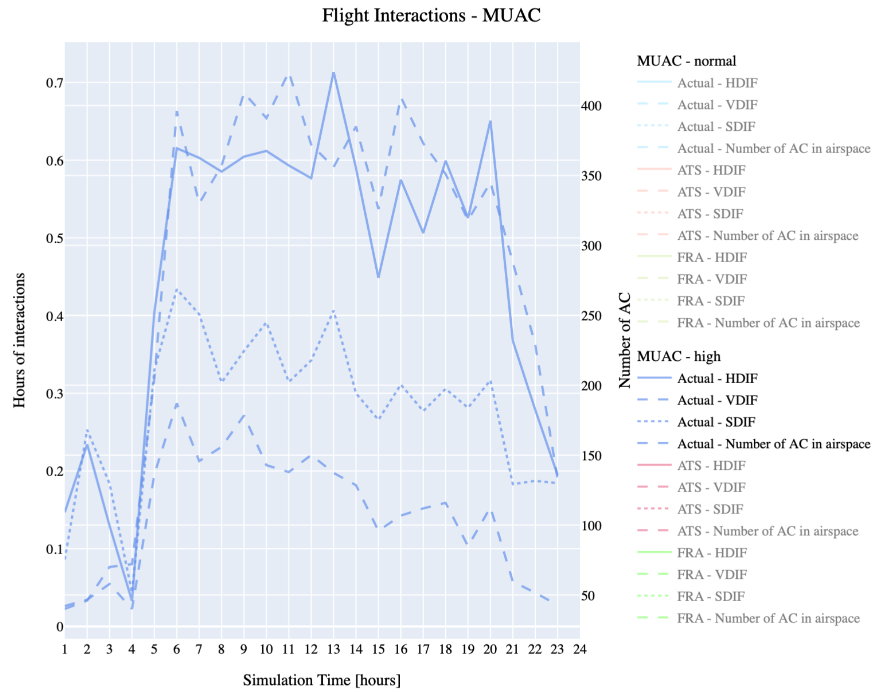
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Dynamic Density - AD and SI - CSE.

3. Complexity Indicators

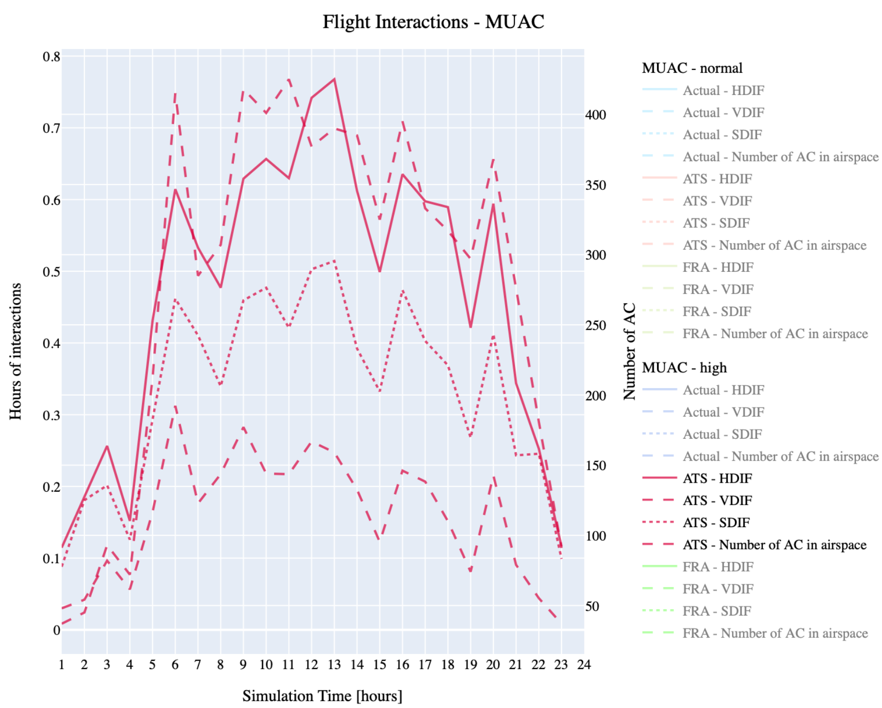
Table 23. Complexity Indicators

Complexity Dimension	**Complexity Indicator**	**Description**
Traffic Density	Adjusted Density	It is measured as possible potential number of interactions between aircraft within an airspace.
Traffic Evolution	Potential Vertical Interactions, VDIF	The evolution of traffic represents the potential interactions between aircraft which are in different phase of the flight. For instance, the potential interactions between climbing, cruising, and descending traffic.
Flow Structure	Potential Horizontal Interactions, HDIF	It indicates the potential interactions caused by the aircraft heading changes.
Traffic Mix	Potential Speed Interactions, SDIF	Based on the traffic speed, it assesses the potential interactions between aircraft.

The complexity indicators are displayed in the study repository: GitHub - Dynamic Density - Indicators. Also, a model of this type plot is shown in Figure 34.

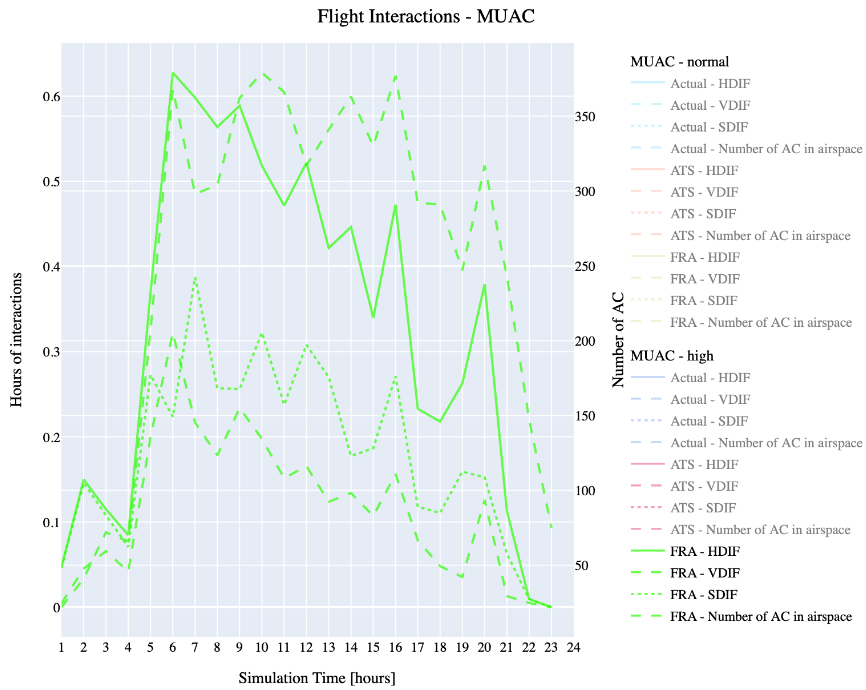


(a) Actual high demand



(b) ATS high demand

Figure 34. Flight Interactions - MUAC



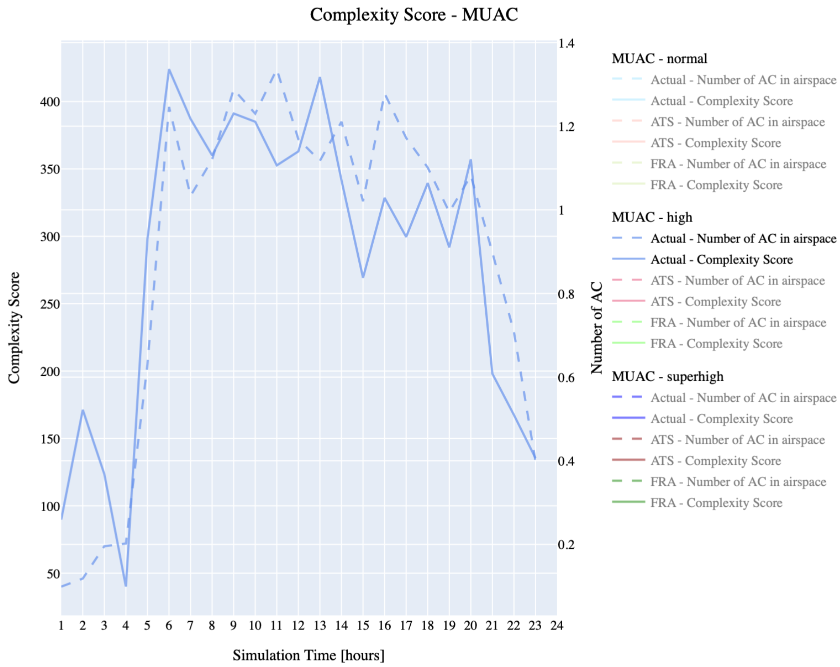
(c) FRA high demand

Figure 34. Flight Interactions - MUAC (cont.)

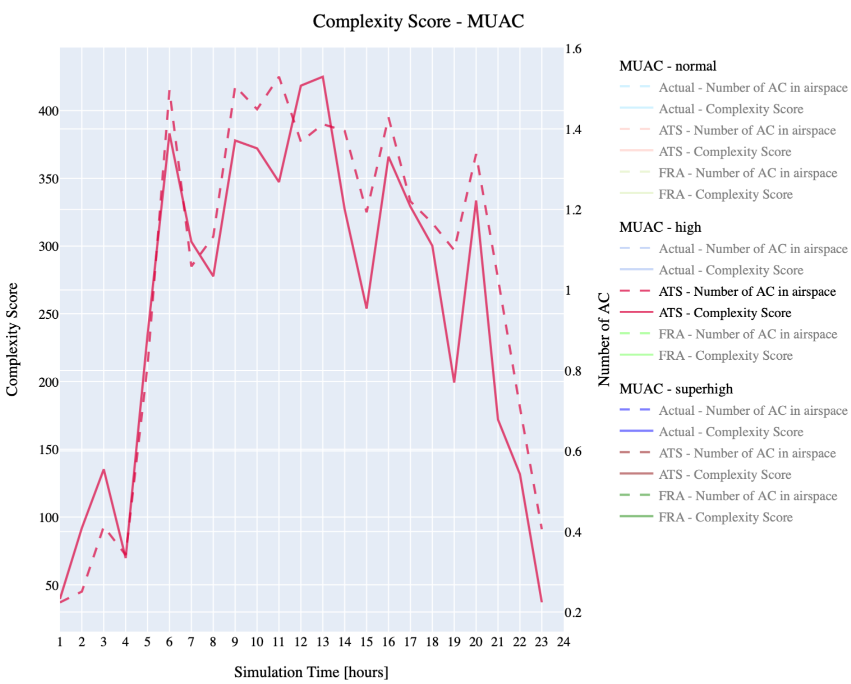
- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Dynamic Density - Indicators - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Dynamic Density - Indicators - MUAC.
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Dynamic Density - Indicators - CSE.

4. Complexity Score - dynamic density

The complexity score is shown in the study repository: GitHub - Dynamic Density - Complexity Score. Also, a model of this type plot is shown in Figure 35.

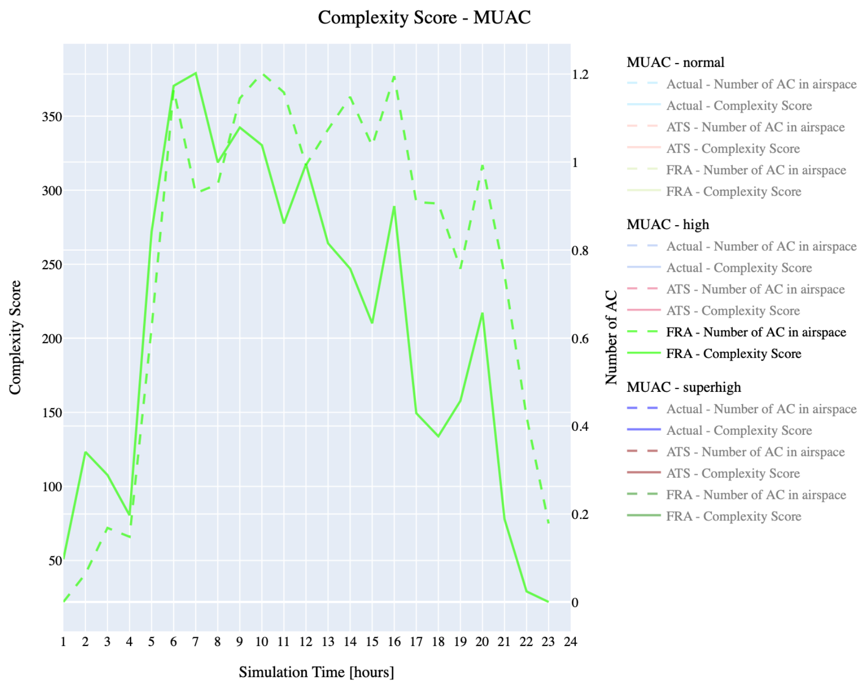


(a) Actual high demand



(b) ATS high demand

Figure 35. Complexity Score vs Number of Aircraft - MUAC



(c) FRA high demand

Figure 35. Complexity Score vs Number of Aircraft - MUAC (cont.)

- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Dynamic Density - Complexity Score - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Dynamic Density - Complexity Score - MUAC.
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Dynamic Density - Complexity Score - CSE.

4.1 Complexity Score Comparison Different Types of Demand - HAN

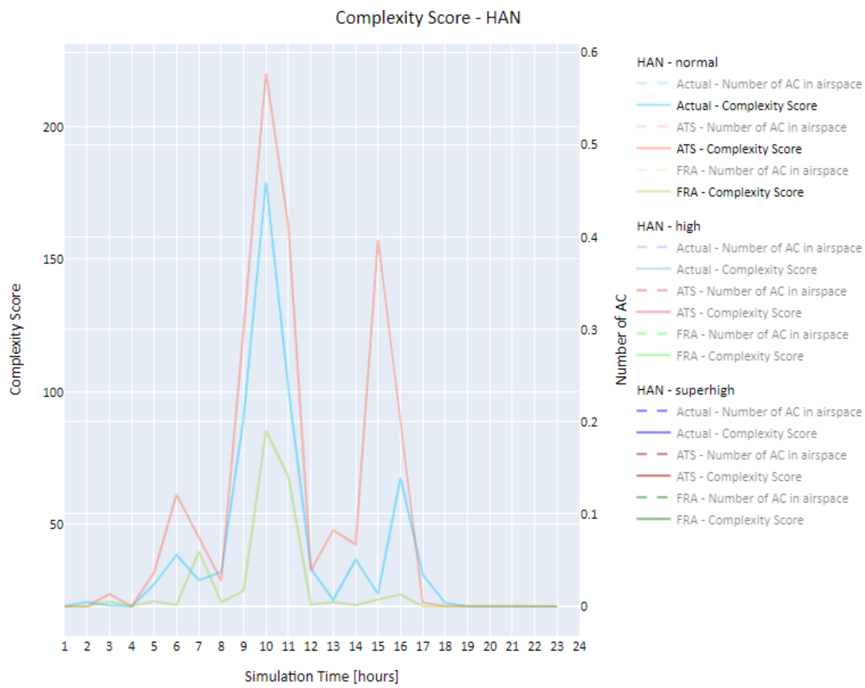


Figure 36. Complexity Score - HAN Normal Demand

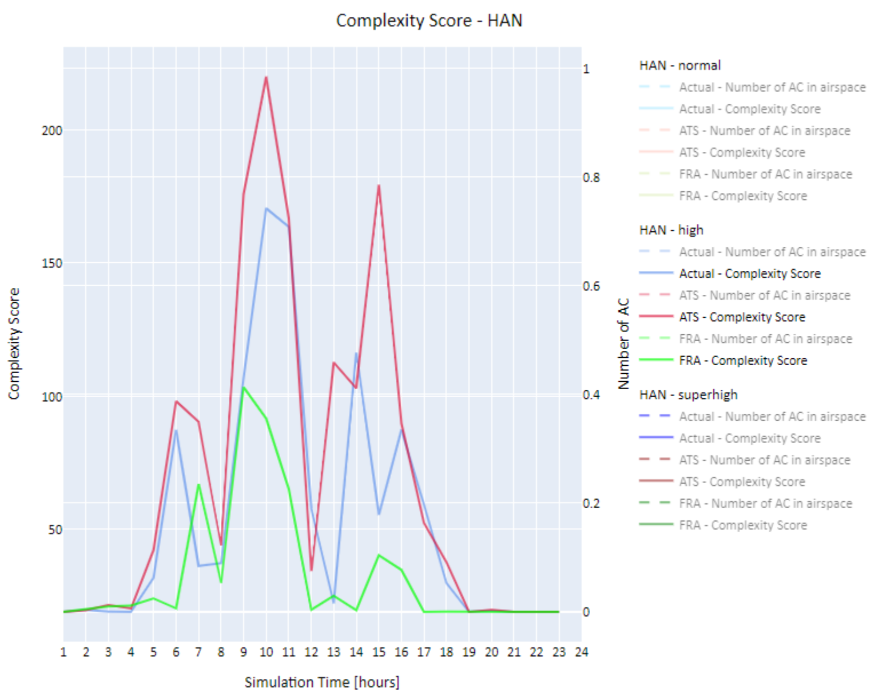


Figure 37. Complexity Score - HAN High Demand

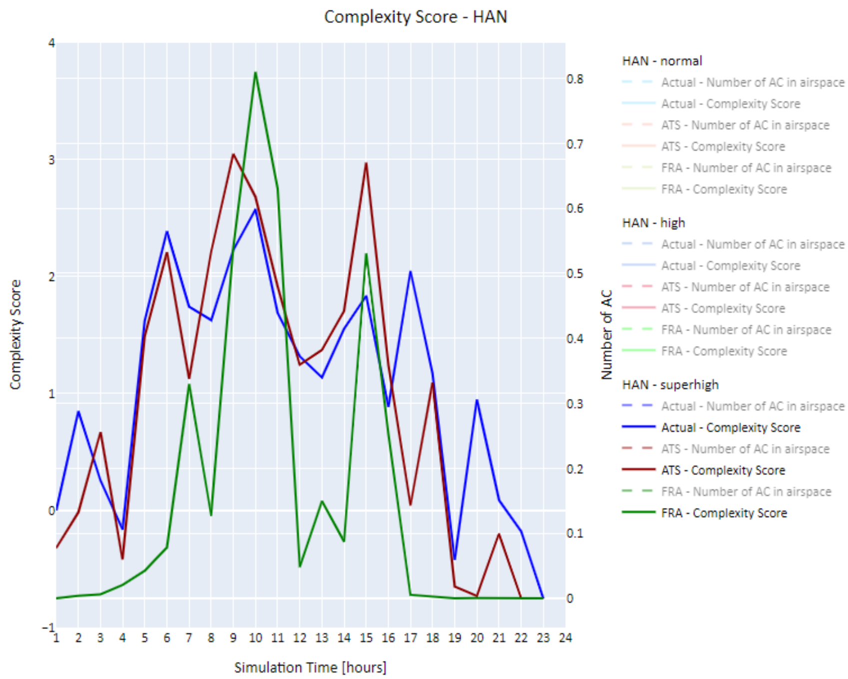


Figure 38. Complexity Score - HAN Super High Demand

5. Correlations between Adjusted Density and the DIF Indicators

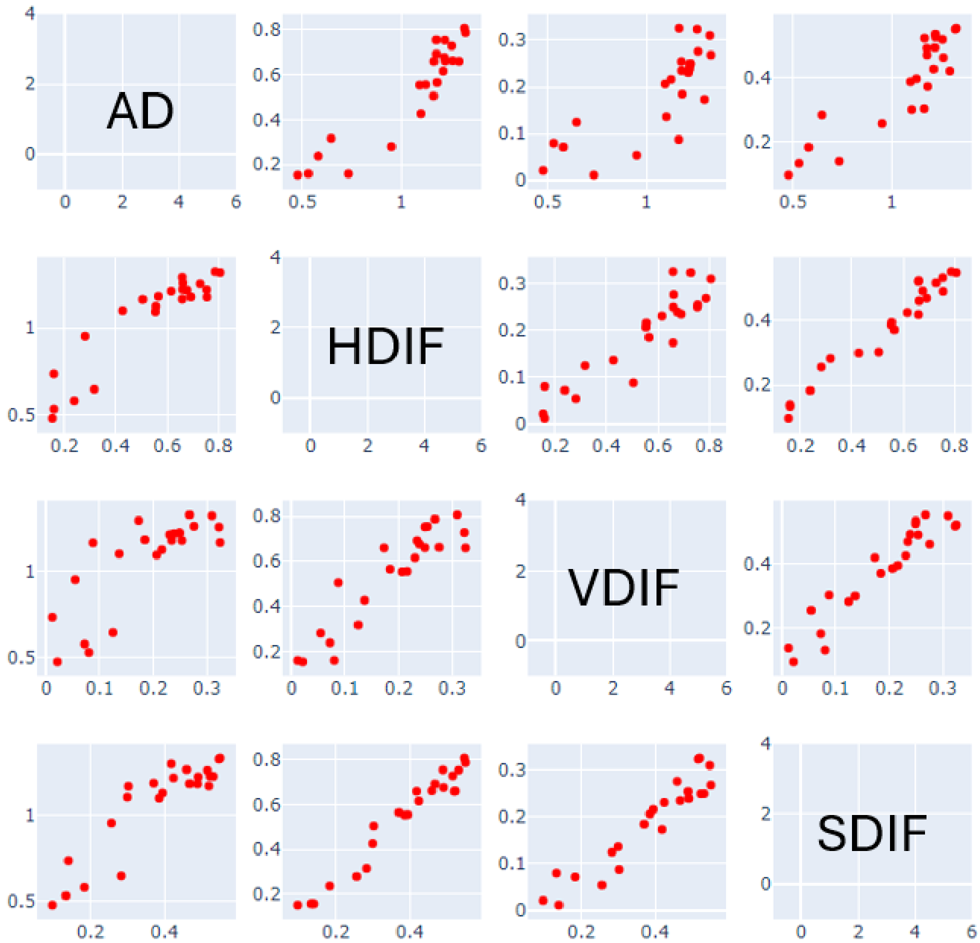


Figure 39. Correlations between Adjusted Density and the DIF Indicators - MUAC ATS Routes Scenario

H. Solution-Space Diagram Implementation

In this section, the computation of SSD is explained. For this implementation, a small example of two aircraft is taking into consideration. Figure 40 illustrates the horizontal view of the aircraft situation. In defining the Solution-Space Diagram it is only takes the unsafe options of changing the heading of the controlled aircraft into consideration to note which aircraft is the controlled one, the aircraft for which the SSD is computed, and the which one is the observed one, the aircraft which will influence the diagram. In Figure 40, blue defines the controlled aircraft and red the observed one. The information of the aircraft are presented in Table 2.

Figure 40. Horizontal view

Before delving into computing the SSD, it is noted that the trajectories of the aircraft meet, so it is assumed to have a conflict. Moreover, both aircraft are flying at the same flight level.

Table 24. Aircraft Information for Conflict Situation

Data Information	**KL204**	**HV6409**
Latitude	N51.0121	N50.87010
Longitude	E003.02195	E001.993114
Flight Level	FL300	FL300
Speed	400kts	350kts
Track	300	030

For the first step in establishing the SSD, it is important to define the safety operational measures. In this study case, the minimum horizontal separation procedure is 5 NM and the minimum vertical separation is 1000 ft. As can be seen in Figure 41, aircraft are flying in an imaginative safety cylinder and any aircraft which come inside this cylinder results in loss of separation violation.

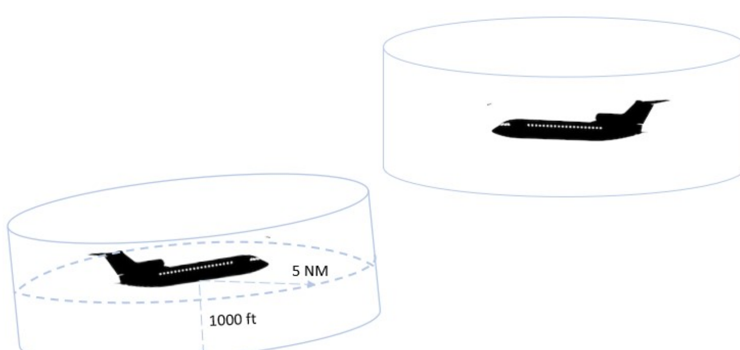


Figure 41. Standard Separation Procedure

Taking this into account, in order to create the SSD, it is first necessary to create the Forbidden Beam Zone, FBZ. This is represented in Figure 42. The orange circle represents the safe area around the observed aircraft which has a radius of 5 NM. The green lines, which are from the controlled aircraft to the observed one, represent the tangents to the circle. The area between these 2 tangents and the separation circle is called FBZ.

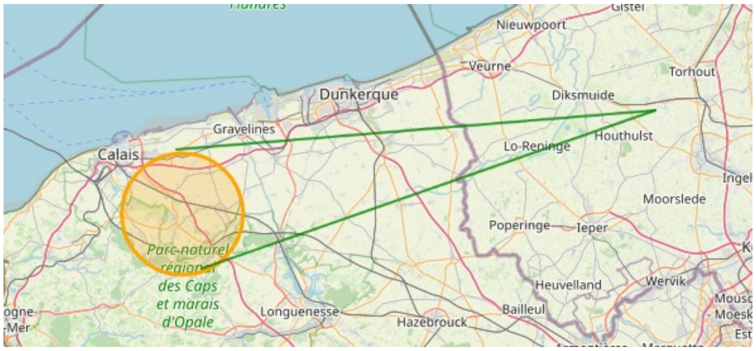


Figure 42. Forbidden Beam Zone

The coordinates of the tangent points are calculated as follows. By knowing the distance and the bearing between both aircraft, the Pythagorean theorem can be applied in the right triangle. Therefore, the distance of the tangent is calculated by using Equation 23.

$$dist_{tangent} = \sqrt{dist^2 - hsep^2}[NM] \tag{23}$$

where dist is the distance between aircraft and hsep is the minimum separation prescribed by ICAO Doc 4444 which is 5 NM. The angle formed by the distance segment and the distance of the tangent is calculated by using Equation 24

$$\alpha = \arcsin \frac{hsep}{dist}[deg] \tag{24}$$

Now, the bearing between the controlled aircraft and the tangent points by adding and subtracting the angle α from the bearing between aircraft can be calculated.

$$\beta_{1,2} = brg \pm \alpha[deg] \tag{25}$$

In order to calculate the tangent points, it is needed to convert the coordinates, which are in the polar coordinates, to Cartesian coordinates. In order to do this, the following system is used:

$$x_{rel} = \begin{bmatrix} dist_{tangent} \cdot \sin(\beta_{1,2}) \\ dist_{tangent} \cdot \cos(\beta_{1,2}) \end{bmatrix} \tag{26}$$

$$x_{rel} = \begin{bmatrix} (lon_{tg_{1,2}} - lon_{con}) \cdot \cos(\frac{lat_{con}+lat_{tg_{1,2}}}{2}) \cdot 60 \\ (lat_{tg_{1,2}} - lat_{con}) \cdot 60 \end{bmatrix} \tag{27}$$

From Equation 26 and Equation 27, the coordinates of both tangents are calculated:

$$\begin{aligned} lat_{tg_{1,2}} &= \frac{dist_{tangent} \cdot \cos(\beta_{1,2})}{60} + lat_{con} \\ lon_{tg_{1,2}} &= \frac{dist_{tangent} \cdot \sin(\beta_{1,2})}{\cos(\frac{lat_{con}+lat_{tg_{1,2}}}{2}) \cdot 60} + lon_{con} \end{aligned} \tag{28}$$

To check if aircraft are in conflict, it is necessary to see if their relative velocity vector is within the FBZ. To do this, both speeds are converted into Cartesian speed vectors and then they are subtracted from each other.

$$V_{rel} = V_{con} - V_{obs} = \begin{bmatrix} V_{con} \cdot \sin TRK_c on - V_{obs} \cdot \sin TRK_{obs} \\ V_{con} \cdot \cos TRK_c on - V_{obs} \cdot \cos TRK_{obs} \end{bmatrix} \tag{29}$$

The velocity vectors are shown in Figure 43. As can be seen in the figure, the relative velocity vector lies inside the FBZ, which means that the two aircraft are in conflict if nothing will be changed.

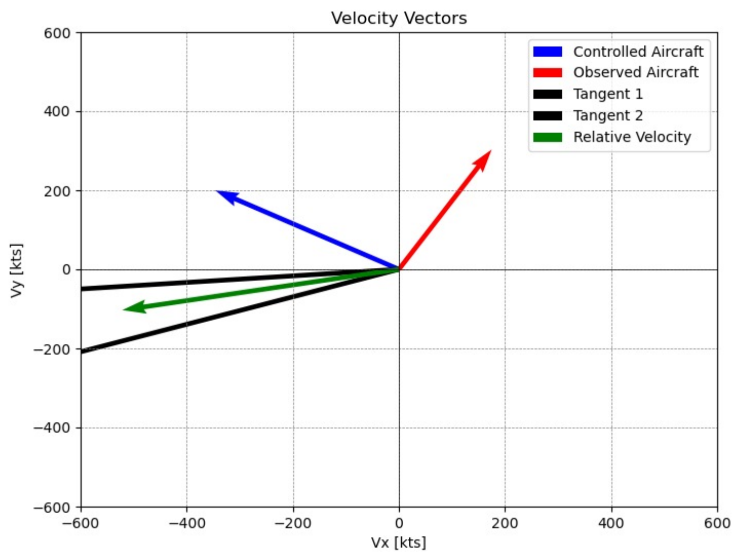


Figure 43. Cartesian relative vectors

To translate the FBZ on the SSD of the controlled aircraft, it is necessary to recalculate the points of the FBZ. Thus, the tip of the FBZ on the diagram corresponds to the magnitude of velocity of the observed aircraft in the direction of the controlled aircraft is seeing it. Then the relative positions of the tangent points are translated. The SSD of controlled aircraft is shown in Figure 44.

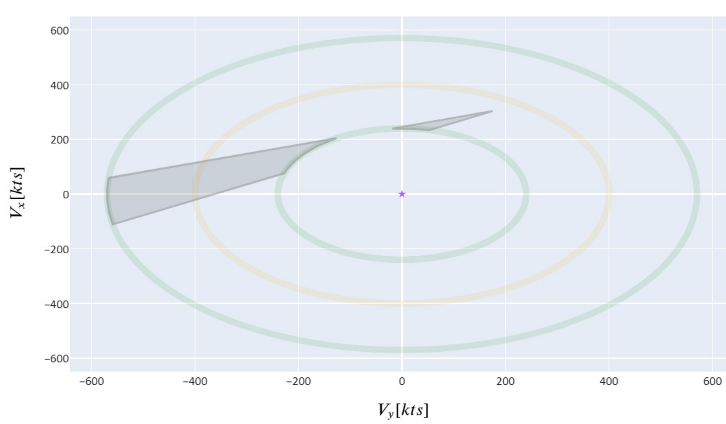


Figure 44. Solution-Space Diagram of controlled aircraft

The green circles represent the minimum and maximum speed of the controlled aircraft based on its performance. For this simple example, the type of the aircraft is Boeing 744, so the minimum speed is 240 kts and the maximum 520 kts. The orange circle represents the actual speed of the controlled aircraft which is 400 kts. The grey area is the unsafe space that the aircraft cannot go.

1. Example of individual Solution-Space Diagram

In this section, two aircraft are displayed as representation of how workload of the controller can be measured per aircraft. The flights are within MUAC airspace on a high demand. The scenario is based on Actual. The full representation of both aircraft on different airspace areas and different demands are displayed in this study repository: GitHub - Controller Workload - SSD.

The information of the two flights are shown below:

1) **Eurowings EWG2596**
   - Departure: Heathrow Airport (EGLL) - London, UK
   - Arrival: Berlin Tegel Airport (EDDT) - Berlin, Germany
   - Aircraft Type: A320
   - Cruise Altitud: FL390
2) **TUI Airways TOM2947**
   - Departure: Manchester Airport (EGCC) - Manchester, UK
   - Arrival: Larnaca International Airport (LCLK) - Larnaca, Cyprus
   - Aircraft Type: B738
   - Cruise Altitud: FL350

Representation of EWG2596

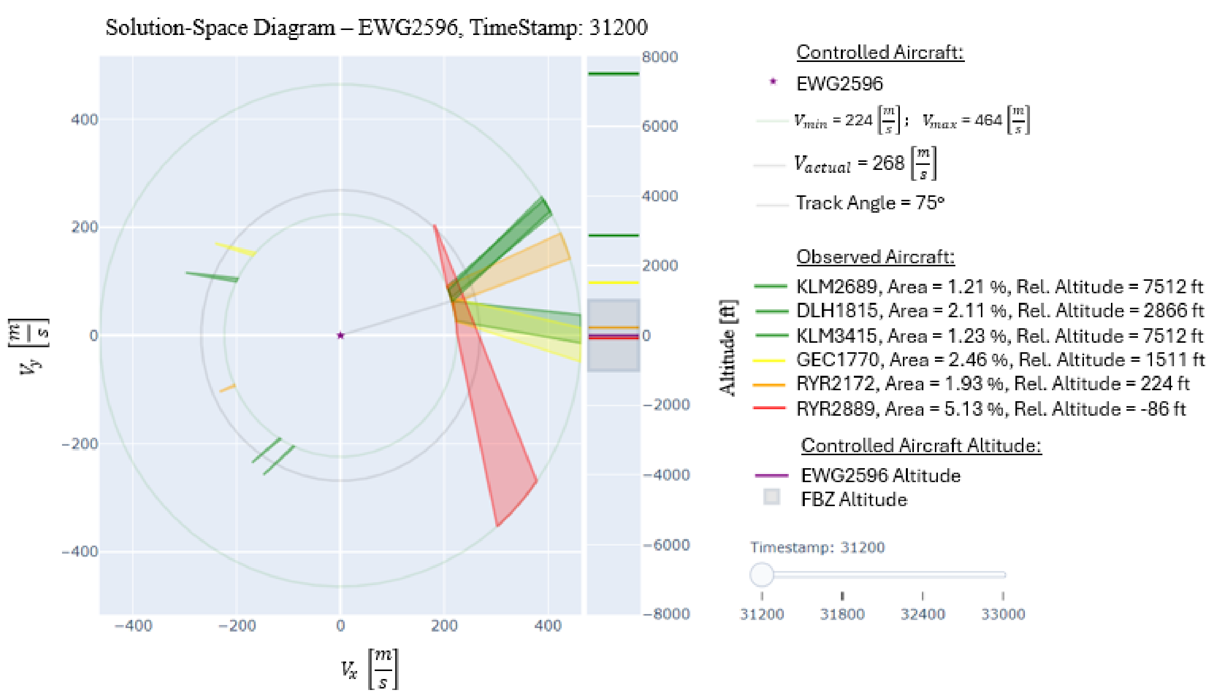


Figure 45. Solution-Space Diagram for EWG2596 first timestamp

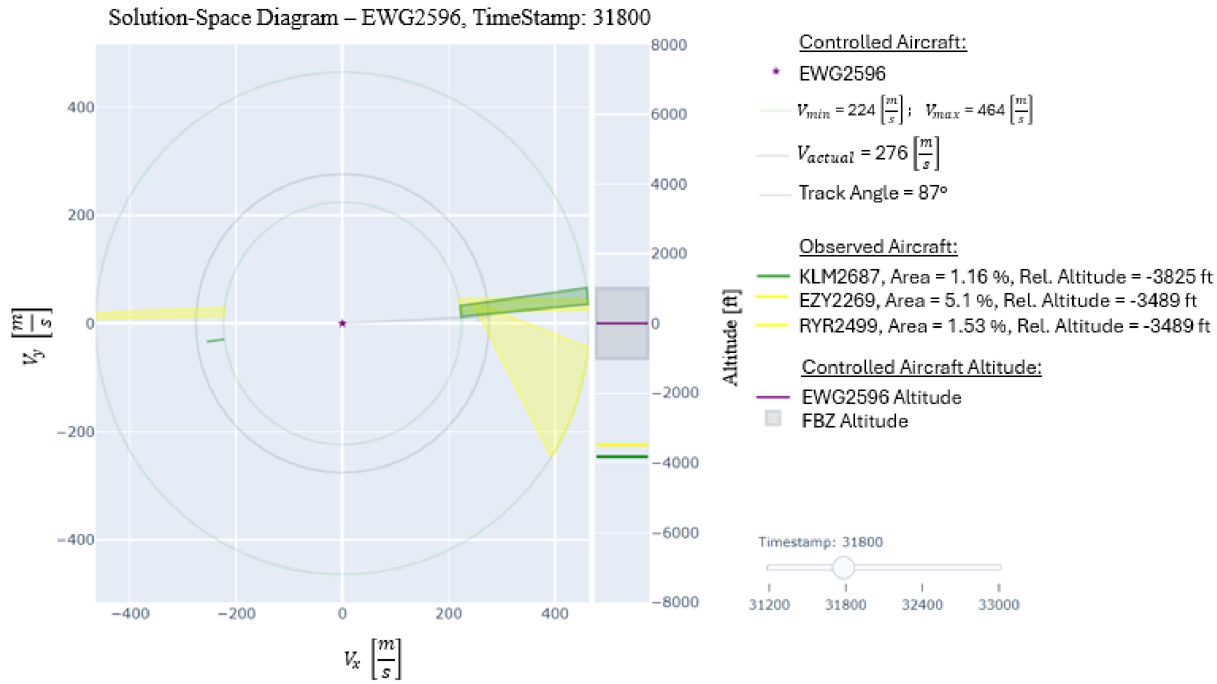


Figure 46. Solution-Space Diagram for EWG2596 second timestamp

- In order to access the interactive SSD for the smallest airspace, HAN, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - EWG2596 - HAN. Here, it can be found SSD representations for ATS Routes and FRA as well.
- In order to access the interactive SSD for the medium airspace, MUAC, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - EWG2596 - MUAC. Here, it can be found SSD representations for ATS Routes and FRA as well.
- In order to access the interactive SSD for the largest airspace, CSE, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - EWG2596 - CSE. Here, it can be found SSD representations for ATS Routes and FRA as well.

Representation of TOM2947

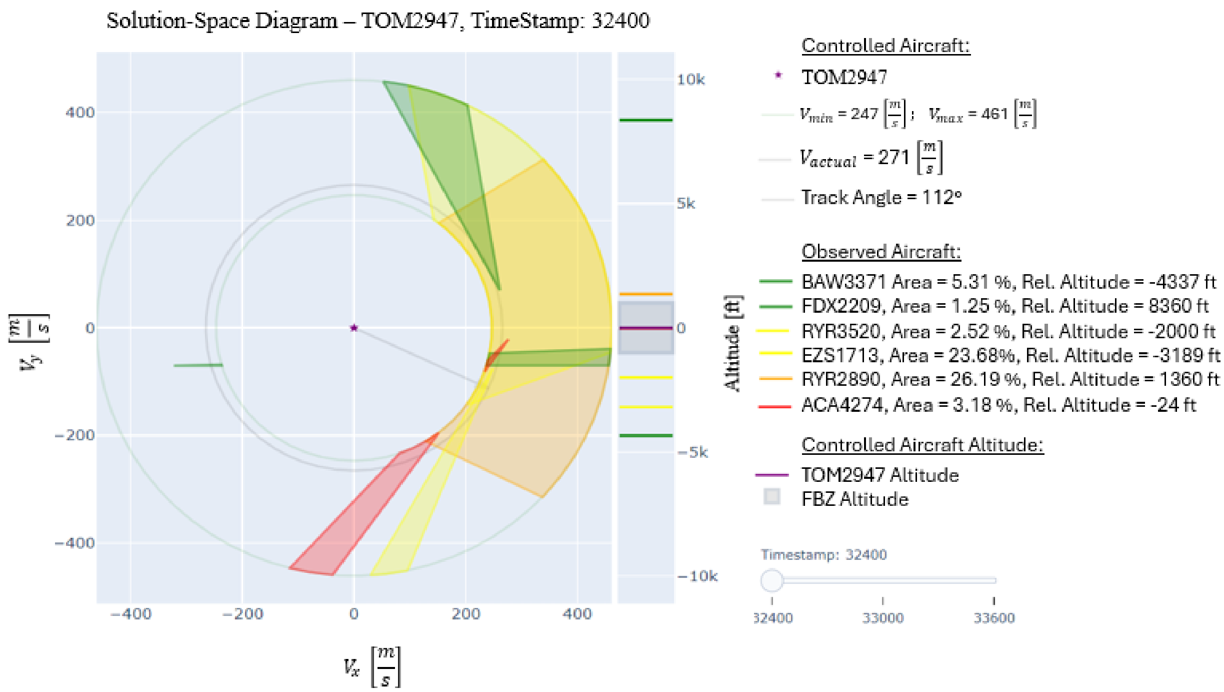


Figure 47. Solution-Space Diagram for TOM2947 first timestamp

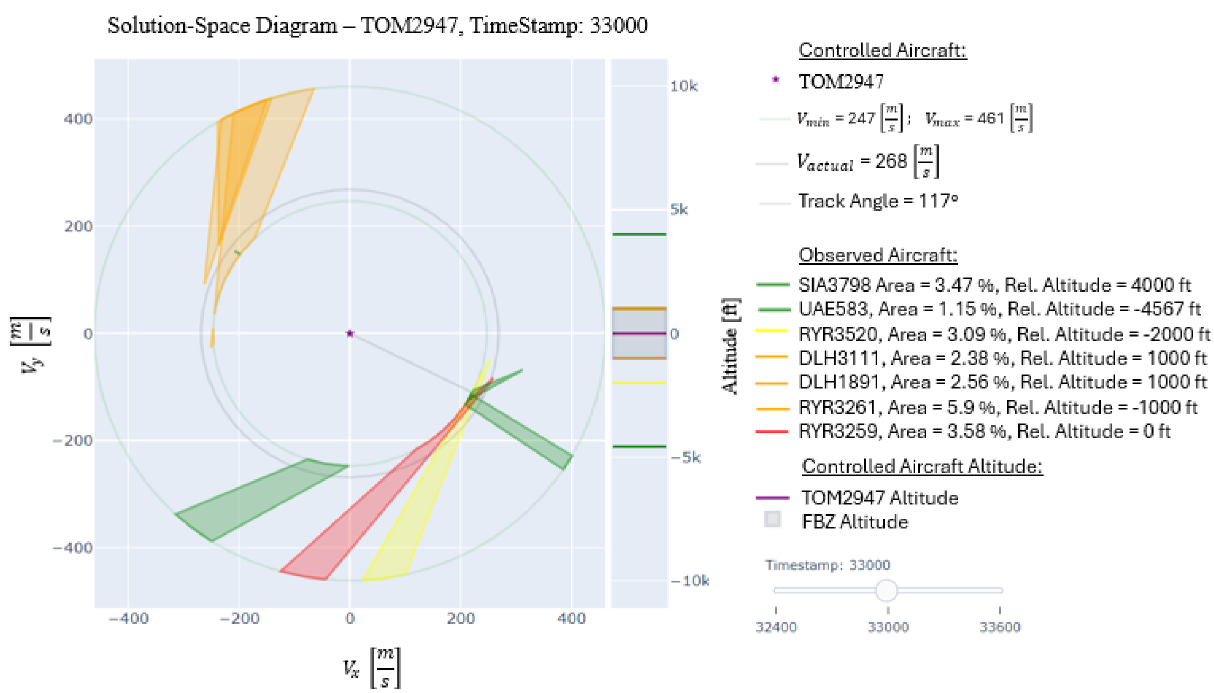


Figure 48. Solution-Space Diagram for TOM2947 second timestamp

- In order to access the interactive SSD for the smallest airspace, HAN, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - TOM2947 - HAN. Here, it can be found SSD representations for ATS Routes and FRA as well.

- In order to access the interactive SSD for the medium airspace, MUAC, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - TOM2947 - MUAC. Here, it can be found SSD representations for ATS Routes and FRA as well.
- In order to access the interactive SSD for the largest airspace, CSE, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - SSD - TOM2947 - CSE. Here, it can be found SSD representations for ATS Routes and FRA as well.

2. Example of Heading and Altitude Options Available

This represents just a simplified version of SSD. Just the actual speed of the aircraft in control is taken into consideration.

Representation of EWG2596

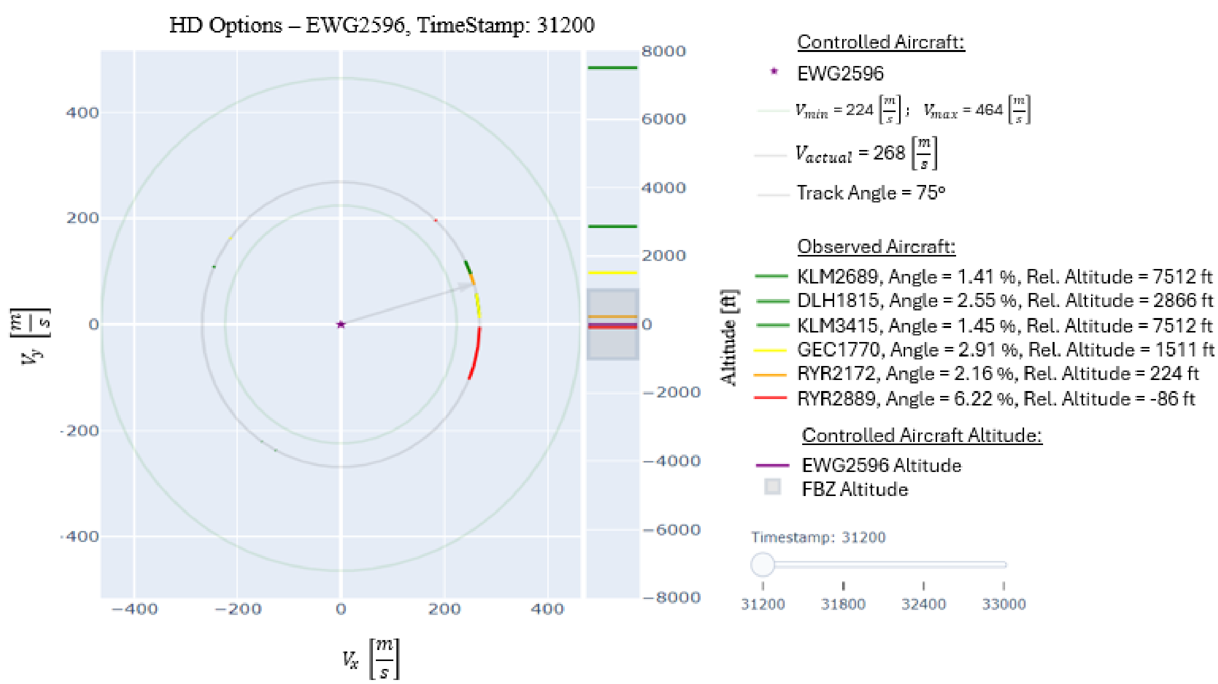


Figure 49. Heading and Altitude Options Diagram for EWG2596 first timestamp

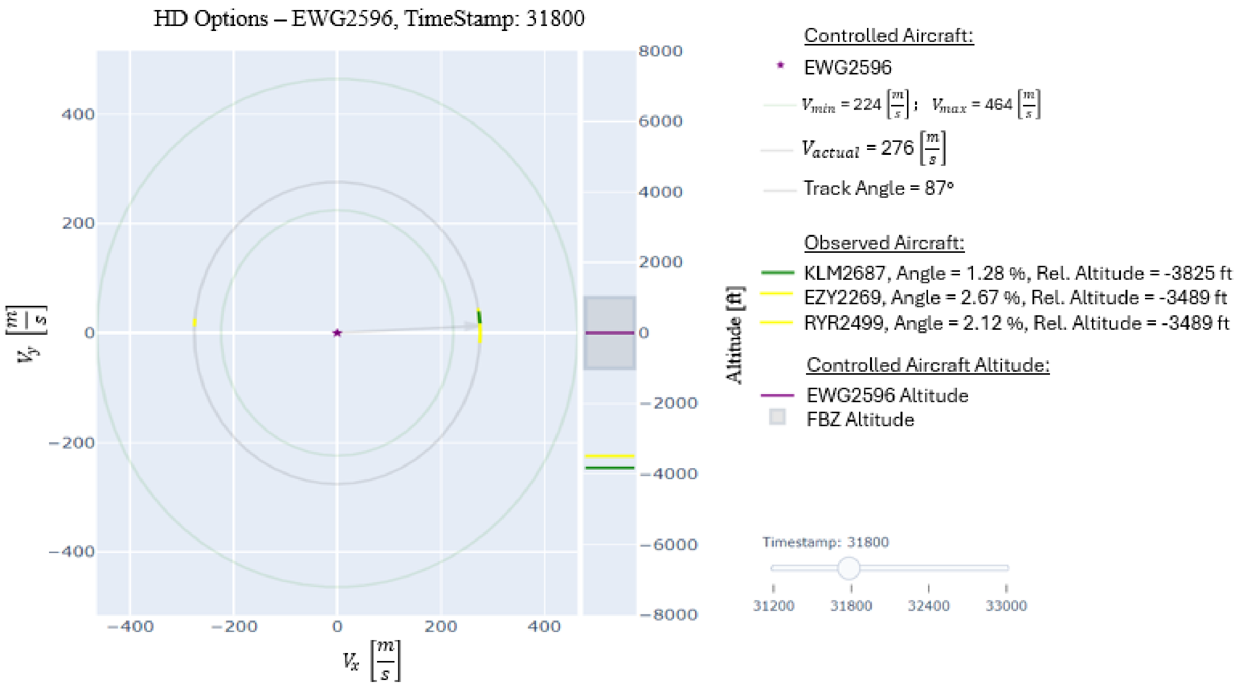


Figure 50. Heading and Altitude Options Diagram for EWG2596 second timestamp

- In order to access the interactive HD for the smallest airspace, HAN, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - HD EWG2596 - HAN. Here, it can be found HD representations for ATS Routes and FRA as well.
- In order to access the interactive HD for the medium airspace, MUAC, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - HD EWG2596 - MUAC. Here, it can be found SSD representations for ATS Routes and FRA as well.
- In order to access the interactive HD for the largest airspace, CSE, for EWG2596, it is necessary to access the repository of this study: GitHub - Controller Workload - HD EWG2596 - CSE. Here, it can be found HD representations for ATS Routes and FRA as well.

Representation of TOM2947

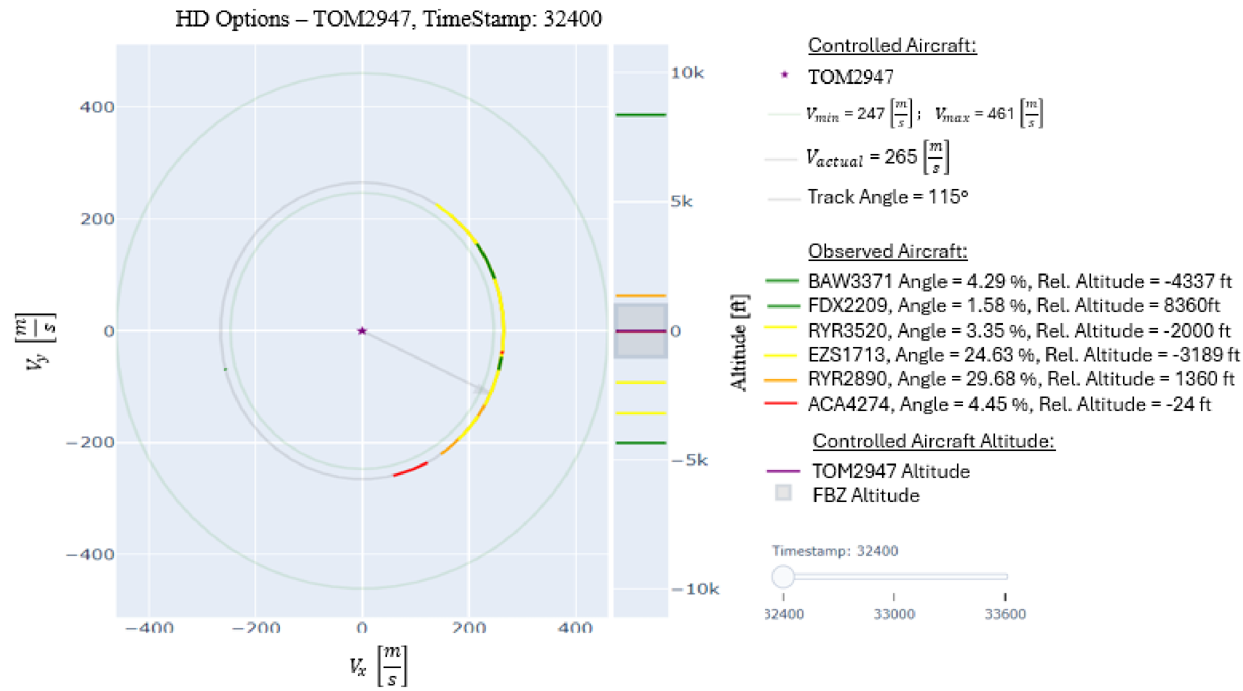


Figure 51. Heading and Altitude Options Diagram for TOM2947 first timestamp

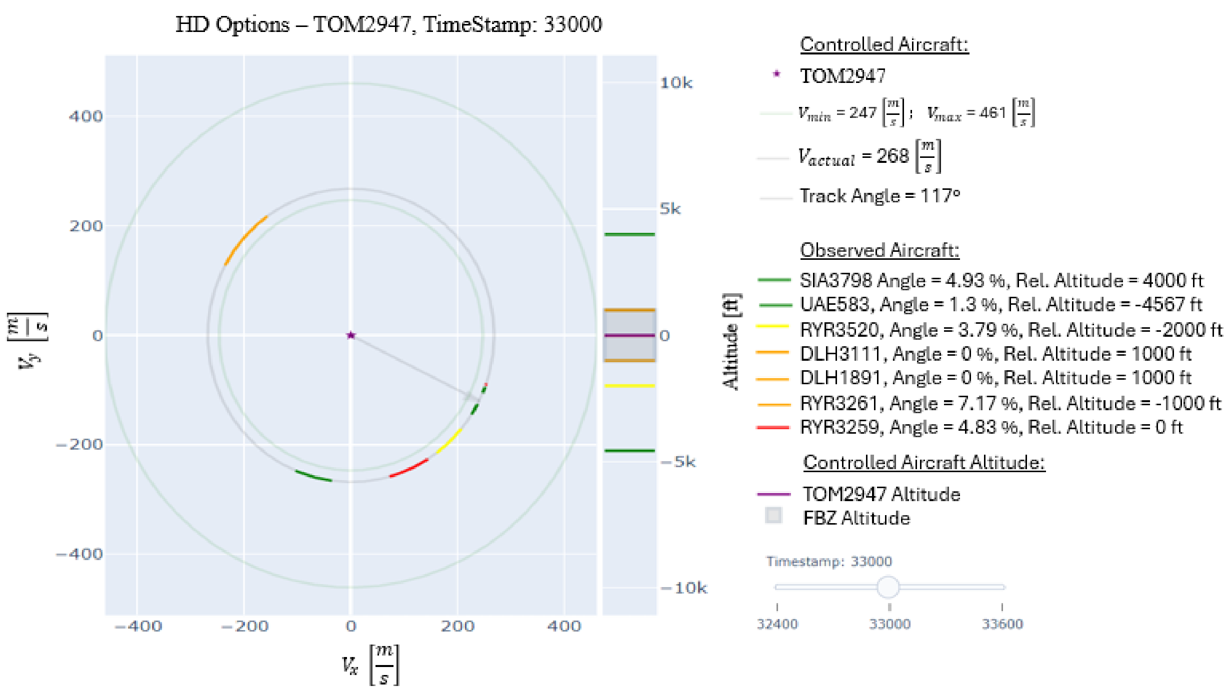
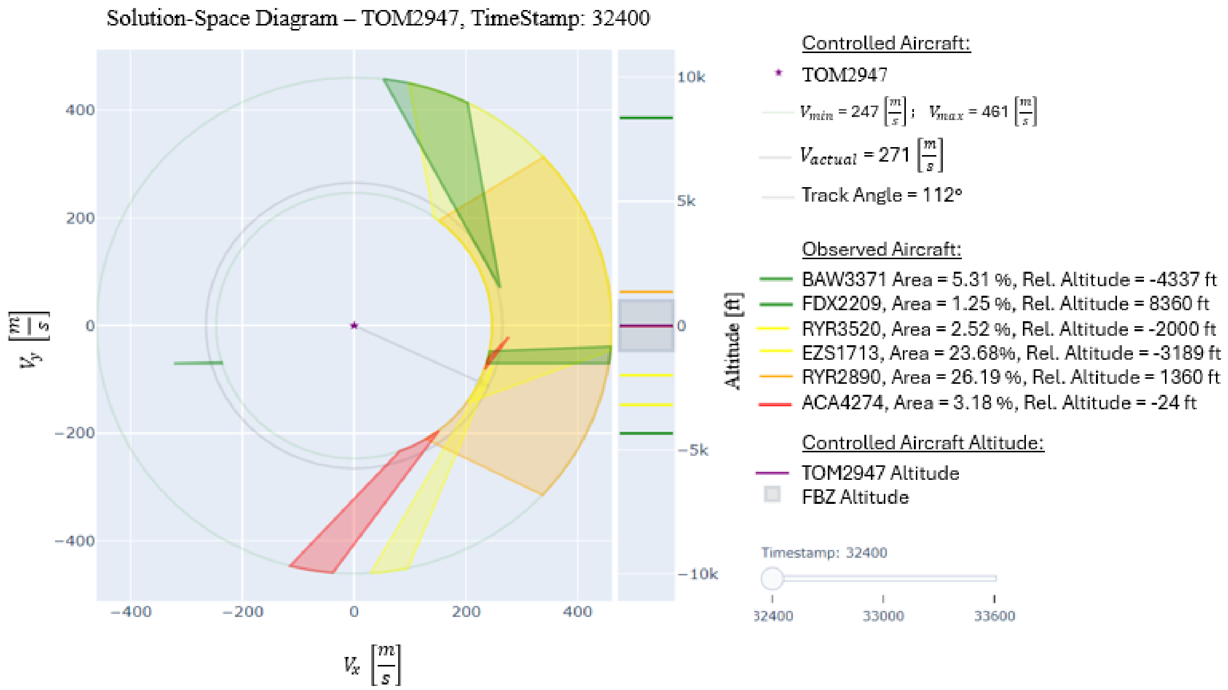


Figure 52. Heading and Altitude Options Diagram for TOM2947 second timestamp

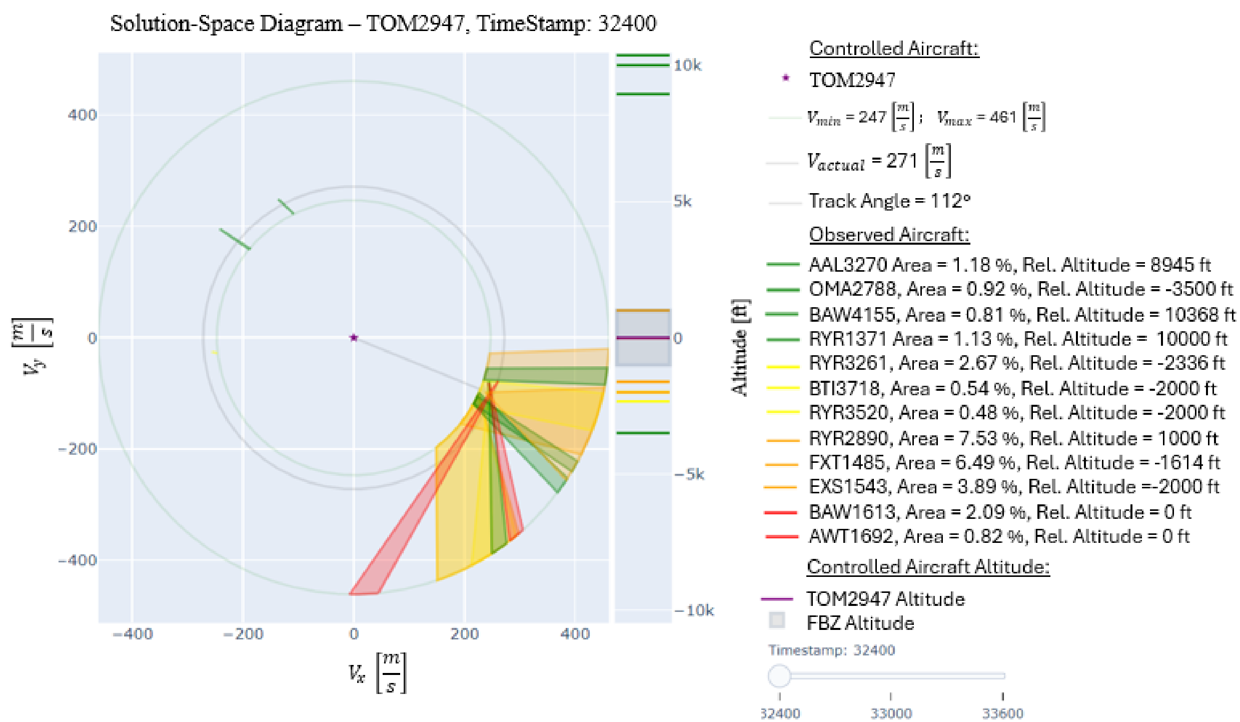
- In order to access the interactive HD for the smallest airspace, HAN, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - HD TOM2947 - HAN. Here, it can be found HD representations for ATS Routes and FRA as well.

- In order to access the interactive HD for the medium airspace, MUAC, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - HD TOM2947 - MUAC. Here, it can be found SSD representations for ATS Routes and FRA as well.
- In order to access the interactive HD for the largest airspace, CSE, for TOM2947, it is necessary to access the repository of this study: GitHub - Controller Workload - HD TOM2947 - CSE. Here, it can be found HD representations for ATS Routes and FRA as well.

3. Comparison of TOM2947 flight through different airspace environments on Solution-Space Diagram

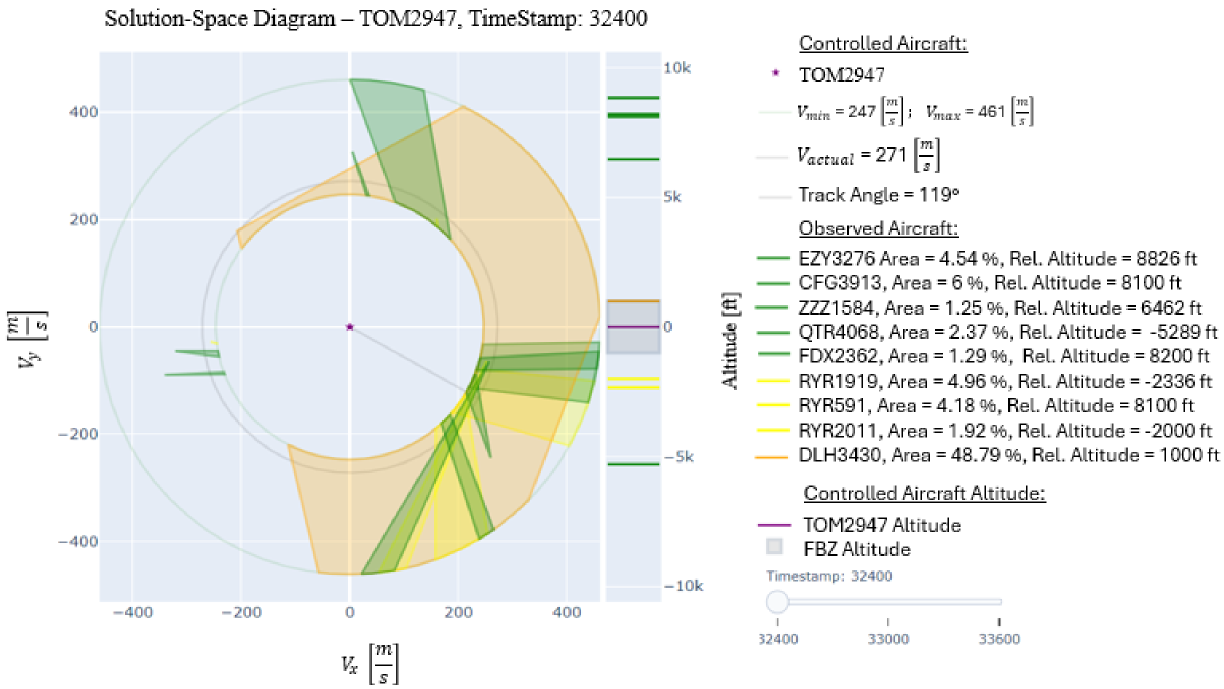


(a) Timestep:09:00 - Actual Trajectory



(b) Timestep:09:00 - ATS Trajectory

Figure 53. Comparison of observed aircraft on SSD for TOM2947 at timestamp 09:00 - MUAC Airspace High Demand

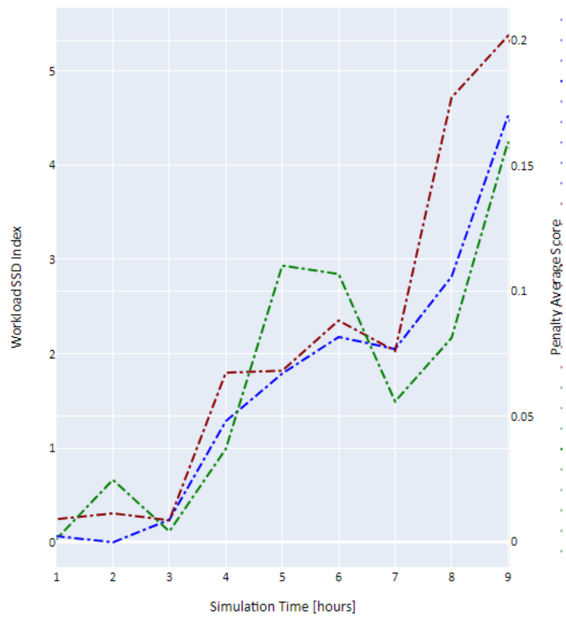


(c) Timestep:09:00 - FRA Trajectory

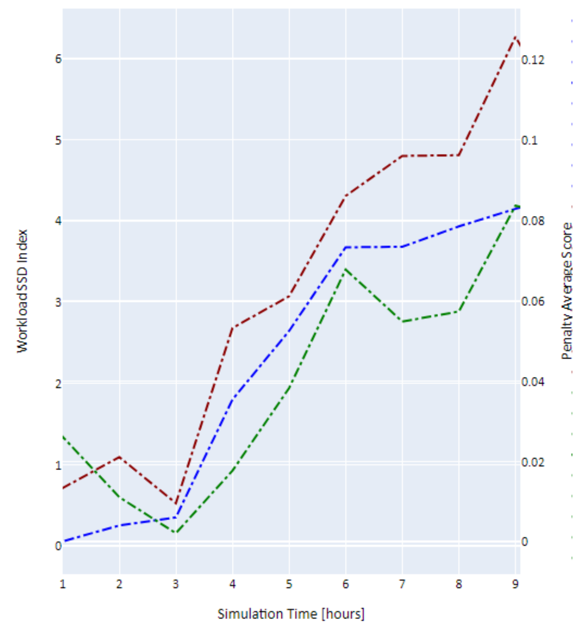
Figure 53. Comparison of observed aircraft on SSD for TOM2947 at timestamp 09:00 - MUAC Airspace High Demand (cont.)

4. Air Traffic Controller Workload Index

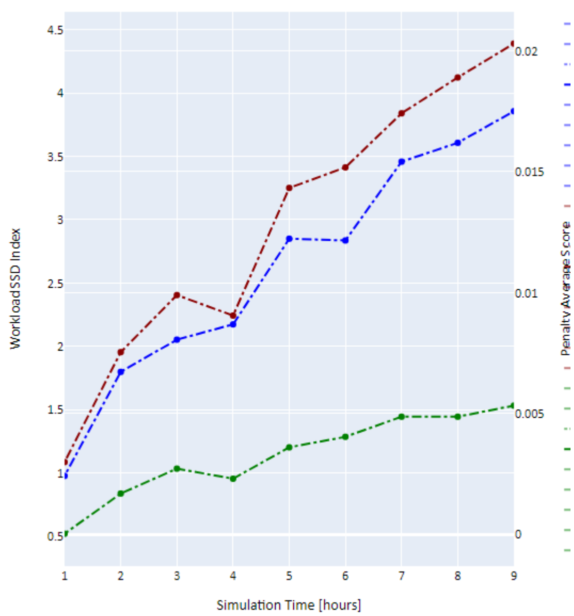
The overall workload index is calculated based on the methodology explained in section IV. For each representation displayed above, a percentage of unsafe area is calculated. The summation of the unsafe area of all the aircraft present in the airspace on timestep *t* divided by the number of aircraft estimates the workload index. This index is shown for the first 8 hours of the simulation for each airspace area in a super high demand in Figure 54.



(a) HAN - Super High Demand



(b) MUAC - Super High Demand



(c) CSE - Super High Demand

Figure 54. Workload Index for first 9 hours of simulation

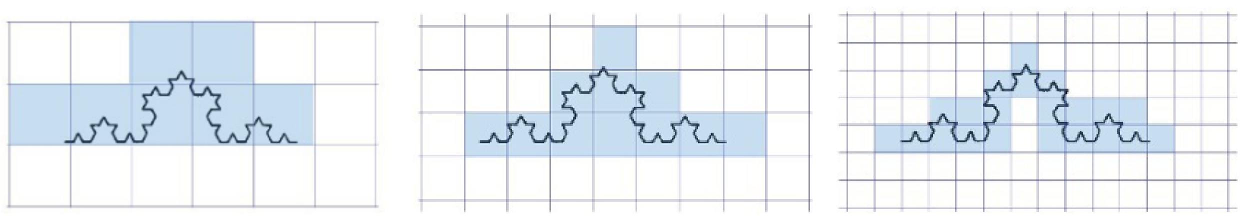
- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Controller Workload - Workload Index - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Controller Workload - Workload Index - MUAC.
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Controller Workload - Workload Index - CSE.

I. Example of Fractal Dimension Calculation

To exemplify how the Box Counting Method works by estimating the fractal dimension, the shape used is obtained from [39]. It is considered the level 2 in the construction of the Koch Curve. Figure 55

Figure 55. Representation of Koch Curve

The number of scales taken in this example is 3. The first grid has a side-length of the box of 24 mm, the second grid has 16 mm and the last scale is 10 mm. The grids are shown in Figure 56.



(a) Grid 24 mm **(b) Grid 16 mm** **(c) Grid 10 mm**

Figure 56. Koch Curve meshed

By applying the counting method, it can be observed that for Figure 56a 7 boxes are covered, in Figure 56b 11 boxes, and in Figure 56c 21. With this information, the slope of a plot of log(box count) versus log(box size) gives the fractal dimension. In this case, the fractal dimension is 1.26.

1. Fractal Dimension

The same principle is applied on each airspace area in each scenario. Hereby, this is an example of griding the MUAC airspace. To have full access to the interactive maps of grids for fractal dimension, please access the repository of this study: GitHub - Fractal Dimension.

Figure 57. Grid used for estimating Fractal Dimension for MUAC - scale = 4.267

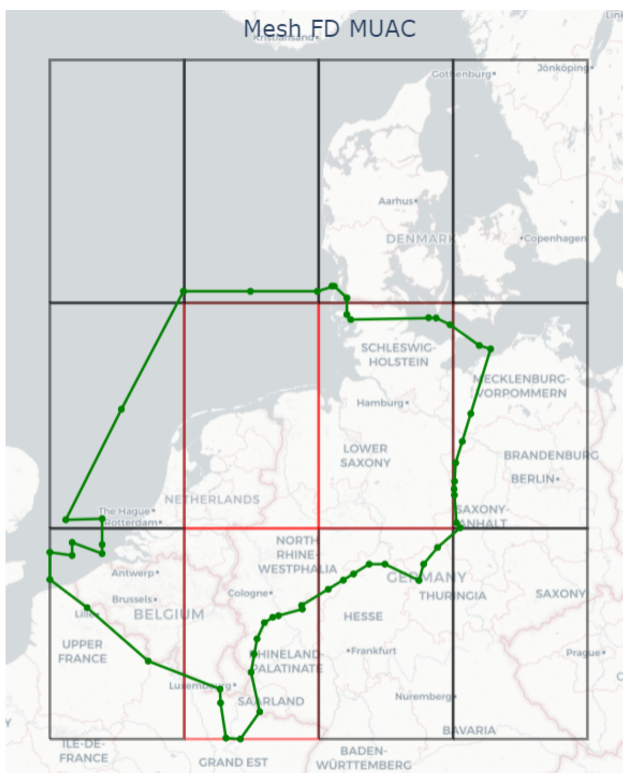


Figure 58. Grid used for estimating Fractal Dimension for MUAC - scale = 3.017

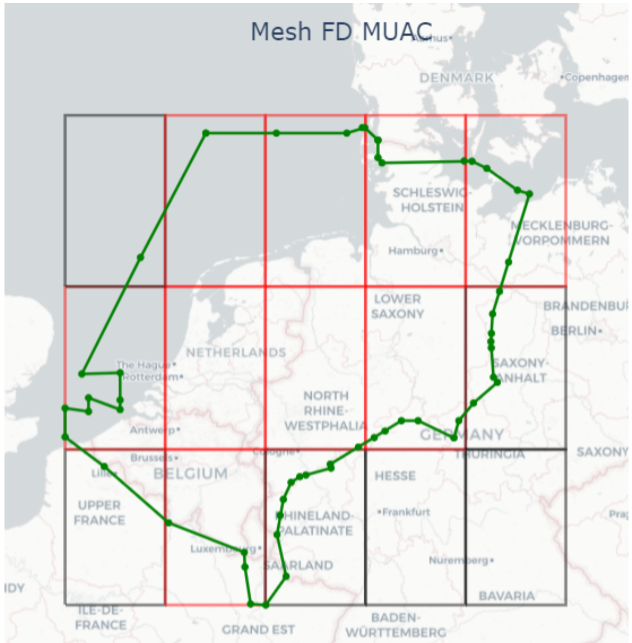


Figure 59. Grid used for estimating Fractal Dimension for MUAC - scale = 2.133

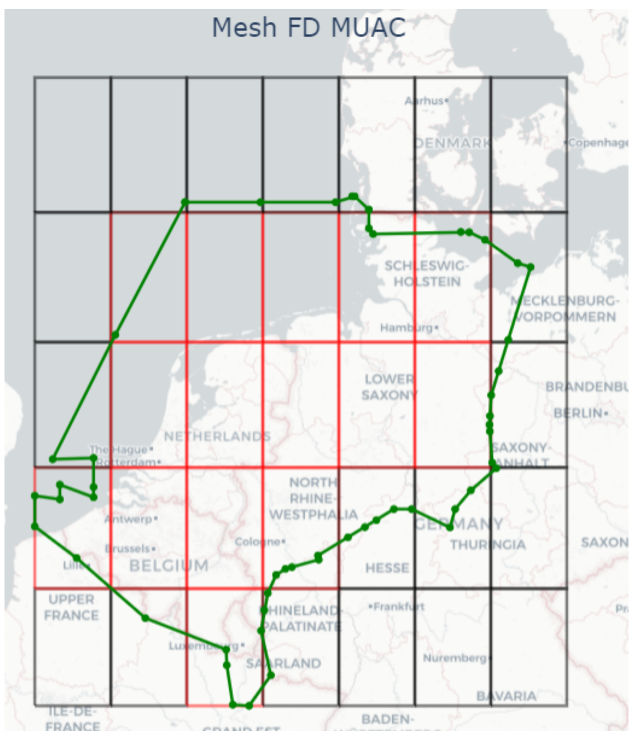


Figure 60. Grid used for estimating Fractal Dimension for MUAC - scale = 1.517

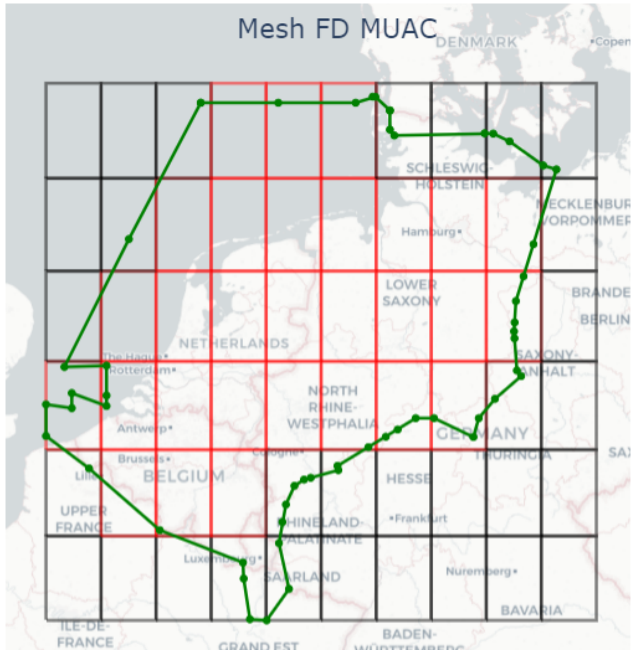


Figure 61. Grid used for estimating Fractal Dimension for MUAC - scale = 1.067

- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Grid - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Grid - MUAC.
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Grid - CSE.

2. Airspace Structure Complexity Index

The complexity can be viewed from the liberty of flights within an airspace area. This can be evaluated by using the box-counting method. The overall complexity index for each airspace area can be seen in the repository of this study: GitHub - Fractal Dimension - Index. In this section, a small example is given.

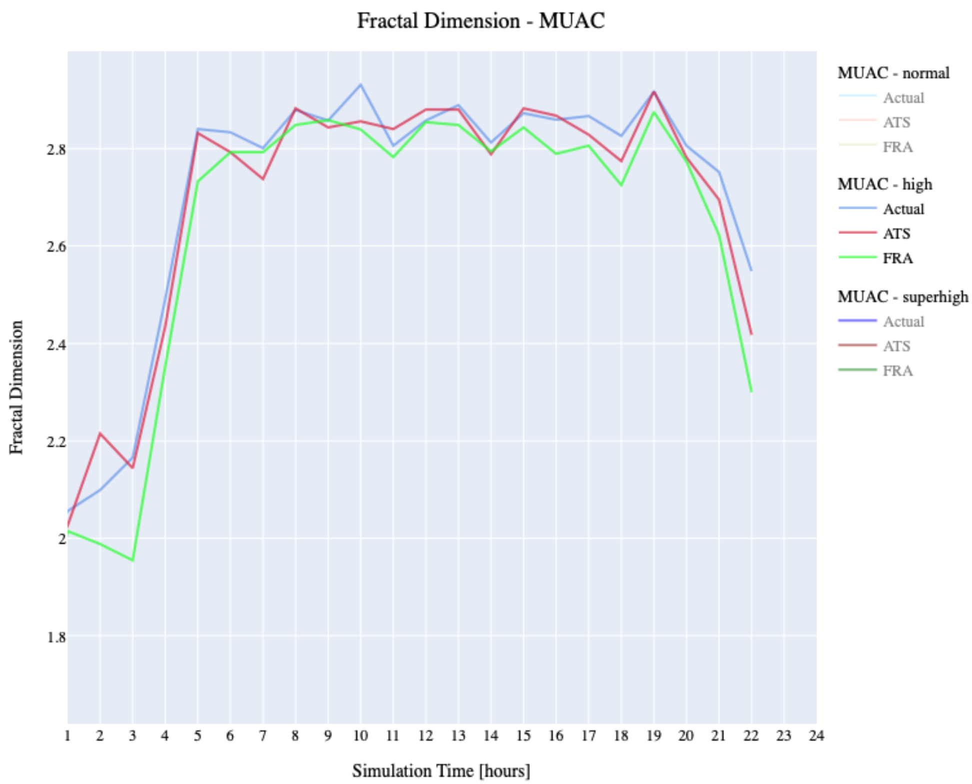


Figure 62. Airspace Structure Complexity Index - MUAC

- In order to access the interactive plot for the smallest airspace, HAN, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Index - HAN.
- In order to access the interactive plot for the medium airspace, MUAC, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Index - MUAC.
- In order to access the interactive plot for the largest airspace, CSE, it is necessary to access the repository of this study: GitHub - Fractal Dimension - Index - CSE.

J. Complexity Plugin

In order to run the complexity plugin within BlueSky, it is important to understand the accessibility of the plugin. Therefore, this plugin includes three complexity metrics calculations. All these metrics are computed within a certain area of interest, area which needs to be defined at the beginning of the plugin via AIRSPACE stack function. The function has three types of input:

- **AIRSPACE OFF** - Type of variable: txt
- It is used to switch off the Experiment Area, and implicit the Traffic Area.
- **AIRSPACE Shapename, bottom, top** - Type of variables: txt, float, float
- The available shapenames are MUAC, HAN, CSE. The bottom and top variables represent the vertical boundaries of the airspace.
- **AIRSPACE lat, lon, lat, lon, bottom, top** - Type of variables: float, float, float, float, float, float
- The resulted airspace is a standard airspace. Two pairs of geographic coordinates together with the vertical boundaries are needed to compute the Experiment and Traffic Areas.

Once the function is called, the Experiment and Traffic Areas are set. The aircraft which are leaving the

Traffic area are deleted and only the aircraft within Experiment Area are counted. AIRSPACE command exports data illustrated in Table 25.

Table 25. Data Exported AIRSPACE

Variable	Description
Simulation Time	Expressed in seconds
Open Experiment Area	It is set to 1 if there is at least one aircraft present in the Experiment Area
Total AC	Number of AC present on the map
AC Present in Neighborhood	Number of AC present in the neighborhood of Experiment Area
AC Present in Traffic Area	Number of AC present in the Traffic Area. Contains traffic from Experiment Area and Neighborhood Area
AC Present in Experiment Area	Number of AC present in Experiment Area
New AC in Experiment Area	If new aircraft arrives in the Experiment Area this variable is set to 1.
Total AC Experiment Area	Total AC which transited the Experiment Area
NB Conflicts Present in Experiment Area	Number of conflicts present in Experiment Area
NB Conflicts Along Track	Count of the Proximate Aircraft Pairs for which the angle between the two trajectories is less than 45°
NB Conflicts Crossing	Count of the Proximate Aircraft Pairs which are neither along track nor opposite
NB Conflicts Opposite	Count of the Proximate Aircraft Pairs for which the angle between the two trajectories is more than 150°
Descending Traffic	Number of AC which are in descending flight phase
Cruising Traffic	Number of AC which are in cruising flight phase
Climbing Traffic	Number of AC which are in climbing flight phase
'NB Levels crossed [FL]	or each aircraft within a sector, the absolute difference between its altitude at sector entry and at sector exit is calculated
Distance Flown in EXP [m]	The distance flown within the Experiment Area

As mentioned above, there are three stack functions dedicated for calculations. The first one is COCA which computes the Different Interactions Flows, DIF, indicators for each cell which belongs to the Experiment Area. This function is updated every 3600 time steps. One time step is considered one second. Once, the metric is called, the function of mesh is created. The function has three types of input:

- **COCA OFF** - Type of variable: txt
- It is used to switch off the metric.
- **COCA Dsize Dalt, Dt, SLAT, SLON, SALT** - Type of variables: float,float,float,int,int,int
- The first two variables give the size of each cell in latitude-longitude and altitude illustrated as well in Figure 29. Dt is the temporal component. Based on this variable the export of data is produced. The SLAT, SLON and SALT variables represent the shift of the mesh. If one of the variables is set to 1 then the shift is produced with an offset of Dsize divided by 2 or of 1000 ft extra for the vertical component.

COCA command exports data illustrated in Table 26.

Table 26. Data Exported COCA

Variable	**Description**
Simulation Time	Expressed in seconds
Cell	Name of the cell that the calculation was made (e.g 0/2/2)
Number of AC in cell	Number of aircraft in the cell
Time Flown	Total time flown by all AC transitioning the cell
Expected duration of potential interactions [hr]	If 2 aircraft fly t_a and t_b minutes in the sector, then the expected duration of potential interactions is the product of both times, $t_a x t_b$
Hours of horizontal interactions [hr]	A horizontal interaction is defined as the simultaneous presence of two aircraft with different headings in a cell.
Hours of vertical interactions [hr]	Takes into consideration just aircraft which are in different flight phase
Hours of speed interactions [hr]	A speed interaction is counted when the difference between the speeds of a pair of aircraft is greater than 35 kts.
NM controlled	Distance flown in the cell

Regarding the second complexity metric, generated by WLSSD command. This is a representation of the Solution-Space Diagram Complexity Index. This metric can be set to be calculated for the whole simulation or just for a specific period of time. Therefore, the input variables of this function are:

- **WLSSD OFF** - Type of variable: txt
- It is used to switch off the metric.
- **WLSSD ON, timestep** - Type of variables: txt, float
- Timestep represents the frequency of measuring the workload. Timestep should be in seconds.
- **WLSSD ON, timestep, start time, end time [sec]** - Type of variables: txt,float,float,float
- Optionally this metric can be calculated just for a period of time. Same as timestep, start time and end time should be in seconds from 1 to 86400.

WLSSD command exports data illustrated in Table 27.

Table 27. Data Exported WLSSD

Variable	**Description**
Simulation Time	Expressed in seconds
Number of aircraft in Experiment Area	Number of AC present in Experiment Area
Number of aircraft in Traffic Area	Number of AC present in Traffic Area
Controlled Aircraft ID	The aircraft ID which is in control by ATCO
Controlled Aircraft Type	Type of aircraft
Controlled Aircraft Track	Direction of controlled aircraft
Controlled Aircraft Altitude	The altitude is expressed in meters
Controlled Aircraft Vactual	The actual groundspeed
Controlled Aircraft Vmin	Based on the aircraft type, this value is determined used the performance open source module within BlueSky and it is expressed in m/s
Controlled Aircraft Vmax	Similar with Vmin, the maximum speed is determined based on the aircraft type. It is expressed in m/s
Controlled Aircraft Penalty	Number of loss of separation
Observed Aircraft Info	Dictionary which include all the observed aircraft that may be in conflict with the controlled aircraft

The last metric available in the complexity plugin is fractal dimension defined by the command FD. This function has default values and calculates the fractal dimension within the Experiment Area. Same as for the COCA command, once FD is called the mesh creation function is called. The input variables are:

- **FD OFF** - Type of variable: txt
- It is used to switch off the metric.
- **FD ON** - Type of variables: txt
- The default values are: scales=5, offsets=off, timestep=300, start time=0, end time=86400.
- **FD scales, offsets, timestep, start time, end time** - Type of variables: float,txt,float,float,float
- Scales variables set the number of grid measurements. Offsets variable is a boolean variable. If the variable is set on 'ON', then six offsets are made. Optionally this metric can be calculated just for a period of time. Timestep, start time and end time should be in seconds from 1 to 86400.

FD command exports data illustrated in Table 28.

Table 28. Data Exported FD

Variable	Description
Simulation Time	Expressed in seconds
Cell	Name of the cell that the calculation was made (e.g 0/2/2)
Offset of cell [lat]	Shift produced in latitude
Offset of cell [lon]	Shift produced in longitude
Offset of cell [alt]	Shift produced in altitude
Size of box	The side-length of the cell
Number of AC in cell	Number of AC present in Experiment Area
Number of AC in airspace	Number of AC present in Experiment Area
Number of conflicts	Number of conflicts inside the cell

K. Simulation Scenarios

All the scenarios that were simulated are displayed in Table 29.

Table 29. Scenarios

Area Name	Airspace Structure	Scenario Type	Simulation Day
HAN	Actual	normal	weekday (Wednesday,6th)
HAN	ATS	normal	weekday (Wednesday,6th)
HAN	FRA	normal	weekday (Wednesday,6th)
HAN	Actual	high	weekday (Wednesday,6th)
HAN	ATS	high	weekday (Wednesday,6th)
HAN	FRA	high	weekday (Wednesday,6th)
HAN	Actual	superhigh	weekday (Wednesday,6th)
HAN	ATS	superhigh	weekday (Wednesday,6th)
HAN	FRA	superhigh	weekday (Wednesday,6th)
MUAC	Actual	normal	weekday (Wednesday,6th)
MUAC	ATS	normal	weekday (Wednesday,6th)
MUAC	FRA	normal	weekday (Wednesday,6th)
MUAC	Actual	high	weekday (Wednesday,6th)
MUAC	ATS	high	weekday (Wednesday,6th)
MUAC	FRA	high	weekday (Wednesday,6th)
MUAC	Actual	superhigh	weekday (Wednesday,6th)
MUAC	ATS	superhigh	weekday (Wednesday,6th)
MUAC	FRA	superhigh	weekday (Wednesday,6th)
CSE	Actual	normal	weekday (Wednesday,6th)
CSE	ATS	normal	weekday (Wednesday,6th)
CSE	FRA	normal	weekday (Wednesday,6th)
CSE	Actual	high	weekday (Wednesday,6th)
CSE	ATS	high	weekday (Wednesday,6th)
CSE	FRA	high	weekday (Wednesday,6th)
CSE	Actual	superhigh	weekday (Wednesday,6th)
CSE	ATS	superhigh	weekday (Wednesday,6th)
CSE	FRA	superhigh	weekday (Wednesday,6th)

L. Airspace Indicators

1. Open Experiment Area Variable
It represents how much the airspace is open in the time of simulation. Open means that at least one aircraft is in the airspace. The interactive plot for each airspace is shown in the repository of this study: GitHub - Airspace Overview - Open.

2. Static Density

The number of aircraft differ in the traffic scenarios due to the fact that once the trajectories are built, when the operational environment is defined, there are some trajectories which do not cross the airspace's borders anymore, especially FRA where there are direct routes. The overview of the number of aircraft in the airspace and also the average time spent by an aircraft inside the area is presented in Table 30

Table 30. Total Number of Aircraft and Time Spent on Average Inside Airspace

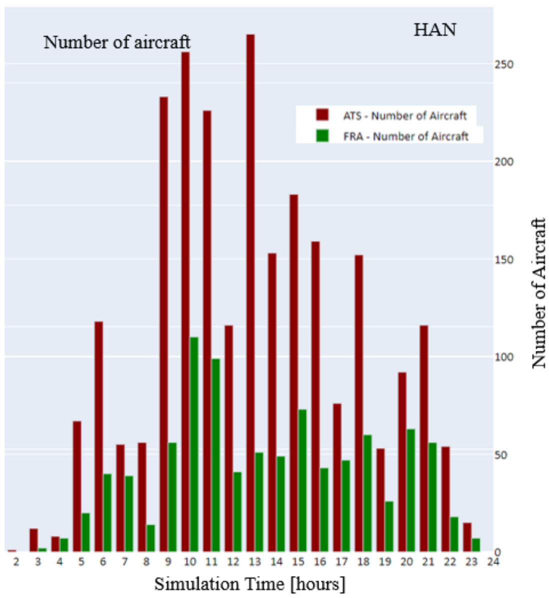
Scenario Name	Total Number of AC	Time Spent on Average
HAN - Actual (n)	1623	13 minutes
HAN - Actual (h)	2502	13 minutes
HAN - Actual (sh)	3543	12.5 minutes
HAN - ATS (n)	1652	14 minutes
HAN - ATS (h)	2544	14 minutes
HAN - ATS (sh)	3256	13 minutes
HAN - FRA (n)	1652	14 minutes
HAN - FRA (h)	2544	14 minutes
HAN - FRA (sh)	3256	13 minutes
MUAC - Actual (n)	3997	20 minutes
MUAC - Actual (h)	6622	18 minutes
MUAC - Actual (sh)	8890	18 minutes
MUAC - ATS (n)	3992	21.5 minutes
MUAC - ATS (h)	3608	20 minutes
MUAC - ATS (sh)	6622	19 minutes
MUAC - FRA (n)	3608	20 minutes
MUAC - FRA (h)	5825	18 minutes
MUAC - FRA (sh)	7837	18 minutes
CSE - Actual (n)	4424	34 minutes
CSE - Actual (h)	6714	35 minutes
CSE - Actual (sh)	8994	35 minutes
CSE - ATS (n)	4622	35 minutes
CSE - ATS (h)	7001	35.5 minutes
CSE - ATS (sh)	9006	35.6 minutes
CSE - FRA (n)	2629	32 minutes
CSE - FRA (h)	3995	33 minutes
CSE - FRA (sh)	5361	33 minutes

A representation of the static density for both Neighborhood and Experiment Area for each airspace can be found in the repository of this study GitHub - Airspace Overview - Static Density. For each airspace area, the plot consists of dividing the variable in airspace structure type within categories of demands.

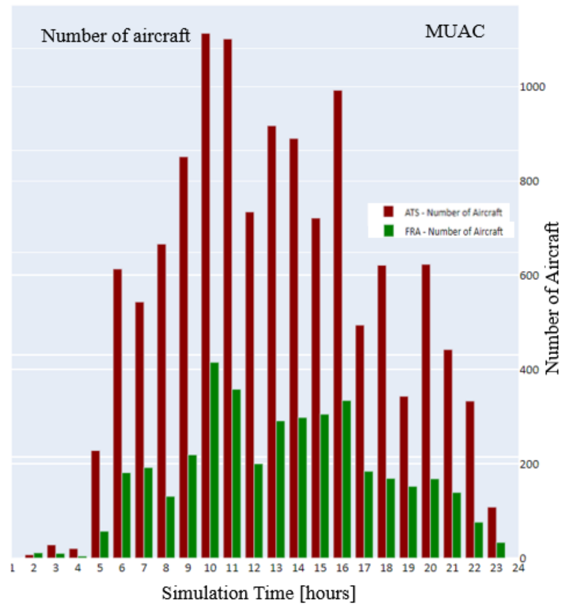
3. Neighborhood Traffic
This indicator shows the traffic around the Experiment Area. It can also offer the minimum and maximum number of aircraft in the neighborhood. These limits are called thresholds. The interactive plots are found in the repository of this study: GitHub - Airspace Overview - Neighborhood Traffic.

4. Experiment Area Traffic
This indicator shows the traffic inside the Experiment Area. It can also offer the minimum and maximum number of aircraft within airspace. These limits are called thresholds. The interactive plots are found in the repository of this study: GitHub - Airspace Overview - Experiment Area Traffic.

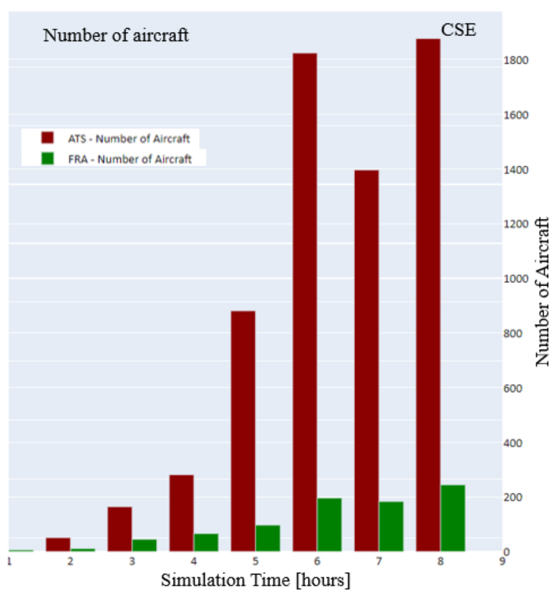
4.1 Number of Aircraft per Hour Super High Demand



(a) HAN - Super High Demand



(b) MUAC - Super High Demand



(c) CSE - Super High Demand

Figure 63. Number of Aircraft per Hour for Super High Demand

5. Entry Counts

The entry counts indicator measures the static density during a given period of time. It is defined as the number of flights entering in the sector during a selected Hourly Entry Count time period. The interactive plots are displayed in the repository of this study: GitHub - Airspace Overview - Entry Counts. In the following, a representation of entry counts for MUAC for different demands is given.

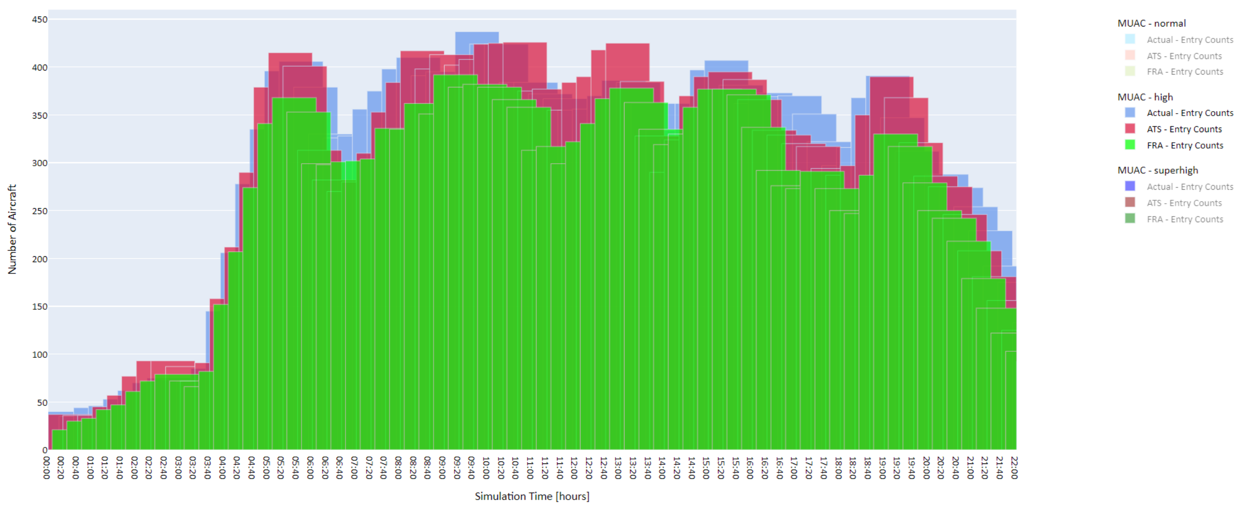


Figure 64. Entry Counts in MUAC - high demand

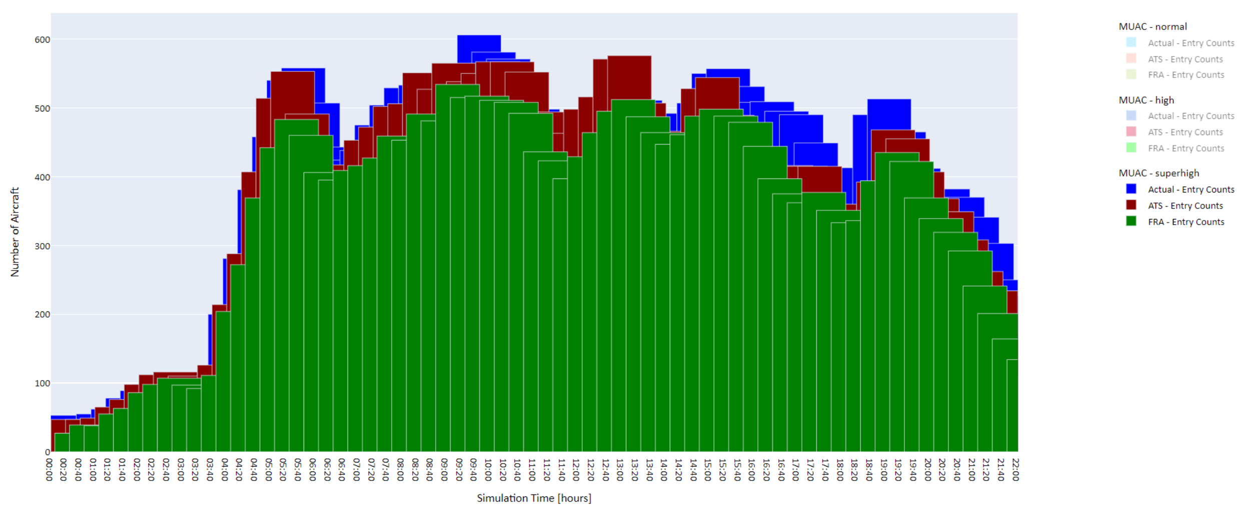


Figure 65. Entry Counts in MUAC - super high demand

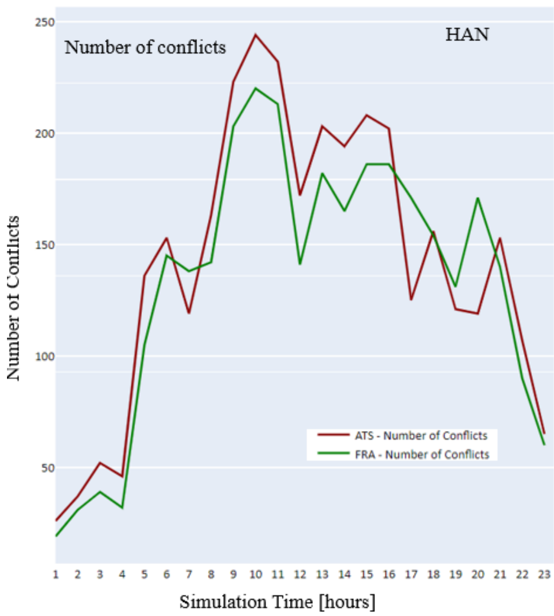
6. Experiment Area Activity

This indicator provides a better picture regarding the activity inside the airspace. It shows the average number of aircraft per hour in the airspace, the average time spent per aircraft and the total number of aircraft entered per hour. The interactive plots are displayed in the repository of this study: GitHub - Airspace Overview - Experiment Area Activity.

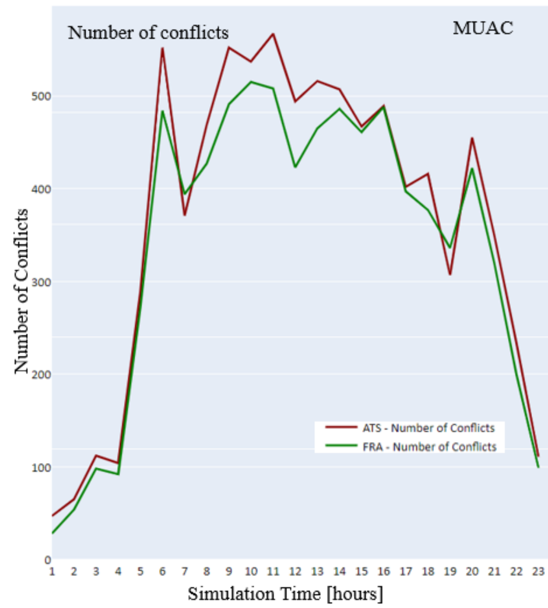
7. Presence of Proximate Aircraft Pairs

This indicator is divided in sub indicators. In order to analyse the overall conflict within the airspace, the relation between number of conflict and number of aircraft is estimated. This plot can be seen in the repository of this study: GitHub - Airspace Overview - Proximate Pairs - Conflicts. For a deeper understanding the overall number of conflicts is splitting and divided by the category of the conflict. Two aircraft can have a conflict along track, opposite direction or when their flight trajectories are crossing. This sub indicator is illustrated as number of conflicts as well as percentage in the repository of this study: GitHub - Airspace Overview - Proximate Pairs - Conflicts Types.

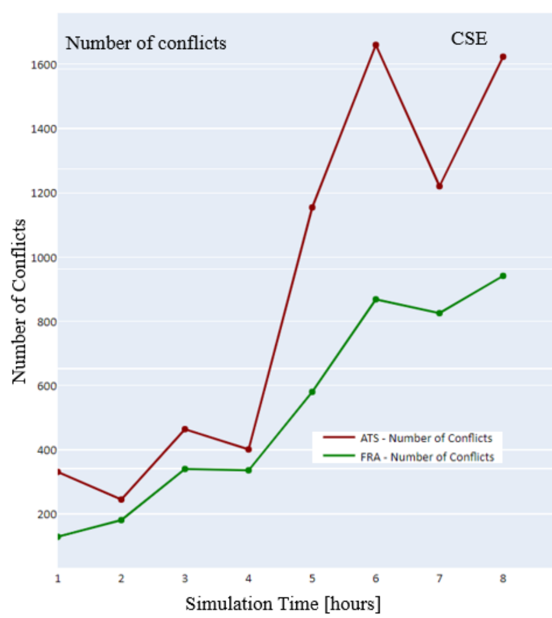
7.1 Presence of Proximate Aircraft Pairs for Super High Demand



(a) HAN - Super High Demand



(b) MUAC - Super High Demand



(c) CSE - Super High Demand

Figure 66. Number of Conflicts for Super High Demand

8. Traffic Phase

Within airspace area, traffic and climb, descend or cruise. The phases of the traffic are based on the vertical speed and not based on the actual profile of the flight. This indicator is illustrated as number of aircraft as well as percentage and it can be found in the repository of this study: GitHub - Airspace Overview - Traffic Phase.

9. Traffic Evolution

This indicator measures the number of flight levels (FL) that an aircraft is passing on average from entry to exit point of the airspace. The interactive plots are displayed in the repository of this study: GitHub - Airspace Overview - Traffic Evolution.

10. Traffic Distribution

In order to understand the traffic dispersion across airspace areas on different airspace structures better, interactive heatmaps on flight levels are made. These plots can be found in the repository of this study: GitHub - Airspace overview - Traffic Distributions.

M. Overall Results

1. HAN

An overview of the performance of the metrics for normal demand is shown in Table 31.

Table 31. Complexity Metrics Performance - HAN (normal)

Metric	Actual	ATS	FRA
Dynamic Density	0.077	0.132	0.027
Workload Index SSD	1.57	2.02	1.67
Workload Index HD	1.8	2.36	1.87
Fractal Dimension	2.01	2.02	1.94
CO2 Emissions	5913.52	5867.59	2563.81

An overview of the performance of the metrics for high demand is shown in Table 32.

Table 32. Complexity Metrics Performance - HAN (high)

Metric	Actual	ATS	FRA
Dynamic Density	0.225	0.313	0.088
Workload Index SSD	2.3	2.98	2.25
Workload Index HD	2.65	3.46	2.51
Fractal Dimension	2.19	2.2	2.1
CO2 Emissions	6563.26	6559.88	2924.3

An overview of the performance of the metrics for super high demand is shown in Table 33.

Table 33. Complexity Metrics Performance - HAN (super high)

Metric	Actual	ATS	FRA
Dynamic Density	0.361	0.355	0.204
Workload Index SSD	3.38	3.7	3.14
Workload Index HD	3.92	4.3	3.53
Fractal Dimension	2.31	2.28	2.22
CO2 Emissions	11218.38	11411.72	5578.88

Table 34. Overall Results HAN Airspace (Normal)

Variable	HAN-Actual-normal	HAN-ATS-normal	HAN-FRA-normal
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	22.98	22.97	22.89
Total AC	1623	1652	1469
Time spent per AC [min]	13.16	13.93	12.63
Normalised Proximate Aircraft Pairs [%]	21.32	35.29	13.26
Along Track [%]	4.82	8.85	2.69
Crossing [%]	8.91	13.6	4.2
Opposite [%]	7.59	12.84	6.37
Traffic Phase Cruising [%]	63	61	55
Traffic Phase Descending [%]	3	3	9
Traffic Phase Climbing [%]	35	36	36
Mix of traffic altitudes	47	48	56
Traffic Evolution [FL]	4.911594543	5.061128297	3.63990526
Adjusted Density	0.63	0.65	0.58
Structural Index	0.08	0.13	0.03
Horizontal Interactions	0.04	0.07	
Vertical Interactions	0.01	0.02	0.0
Speed Interactions	0.02	0.04	0.01
Complexity Score	0.077	0.132	0.027
Overall Penalty Score	0.014418629	0.035763271	0.03301561
SSD Workload Index	(3.047, 2.154, 1.708, 0.807)	(3.880, 2.328, 2.194, 1.276)	(3.832, 1.870, 1.5019, 1.143)
HD Workload Index	(3.363, 2.525, 1.938, 0.94)	(4.4709, 2.705, 2.59, 1.482)	(4.280, 2.056, 1.68, 1.321)
*Fractal Dimensio*n	2.011630435	2.016884058	1.942282609
CO2 Emissions	5913.521336	5867.591931	2563.811262

Table 35. Overall Results HAN Airspace (High)

Variable	HAN-Actual-high	HAN-ATS-high	HAN-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	22.98	22.97	22.89
Total AC	2502	2544	2229
Time spent per AC [min]	13.1	13.8	12.7
Normalised Proximate Aircraft Pairs [%]	36.53	51.89	19.43
Along Track [%]	7.0	12.07	4.71
Crossing [%]	16.68	19.93	5.77
Opposite [%]	12.85	19.89	8.95
Traffic Phase Cruising [%]	63	62	56
Traffic Phase Descending [%]	2	3	9
Traffic Phase Climbing [%]	34	35	35
Mix of traffic altitudes	45	47	55
Traffic Evolution [FL]	4.712511144	4.877313678	3.633065869
Adjusted Density	0.9	0.86	0.76
Structural Index	0.17	0.26	0.08
Horizontal Interactions	0.12	0.17	0.06
Vertical Interactions	0.03	0.04	0.01
Speed Interactions	0.07	0.1	0.02
Complexity Score	0.225	0.313	0.088
Overall Penalty Score	0.020493825	0.063158875	0.04234035
SSD Workload Index	(4.324, 3.146, 2.494, 1.220)	(5.844, 3.618, 3.122, 1.832)	(5.276, 2.64, 2.11, 1.392)
HD Workload Index	(4.791, 3.681, 2.890, 1.41)	(6.715, 4.181, 3.713, 2.1027)	(5.850, 2.92, 2.374, 1.567)
Fractal Dimension	2.19173913	2.196775362	2.104528986
CO2 Emissions	6563.259623	6559.883803	2924.297867

Table 36. Overall Results HAN Airspace (Super High)

Variable	HAN-Actual-high	HAN-ATS-high	HAN-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	23.0	22.97	22.93
Total AC	3543	3256	3064
Time spent per AC [min]	12.5	13.36	11.9
Normalised Proximate Aircraft Pairs [%]	62.4	75.77	30.09
Along Track [%]	10.44	16.06	7.89
Crossing [%]	25.05	29.52	10.07
Opposite [%]	26.91	30.19	12.13
Traffic Phase Cruising [%]	66	67	56
Traffic Phase Descending [%]	4	3	12
Traffic Phase Climbing [%]	30	30	32
Mix of traffic altitudes	44	43	57
Traffic Evolution [FL]	4.730695926	4.633587138	3.485914924
Adjusted Density	0.53	0.56	0.91
Structural Index	0.67	0.57	0.16
Horizontal Interactions	0.2	0.18	0.13
Vertical Interactions	0.05	0.05	0.03
Speed Interactions	0.12	0.12	0.05
Complexity Score	0.361	0.355	0.204
Overall Penalty Score	0.034197604	0.077105162	0.059476444
SSD Workload Index	(5.316, 4.079, 3.987, 2.093)	(6.66, 4.33, 4.09, 2.35)	(6.549, 3.527, 3.111, 2.112)
HD Workload Index	(5.973, 4.73, 4.621, 2.463)	(7.62, 5.045, 4.81, 2.69)	(7.157, 3.944, 3.535, 2.413)
Fractal Dimension	2.314021739	2.281557971	2.223333333
CO2 Emissions	11218.37874	11411.72319	5578.879545

2. MUAC

An overview of the performance of the metrics for normal demand is shown in Table 37.

Table 37. Complexity Metrics Performance - MUAC (normal)

Metric	Actual	ATS	FRA
Dynamic Density	1.138	1.257	0.609
Workload Index SSD	2.09	2.77	2.03
Workload Index HD	2.34	3.1	2.22
Fractal Dimension	2.51	2.52	2.44
CO2 Emissions	25537.86	25507.52	13561.67

An overview of the performance of the metrics for high demand is shown in Table 38.

Table 38. Complexity Metrics Performance - MUAC (high)

Metric	Actual	ATS	FRA
Dynamic Density	0.982	1.084	0.715
Workload Index SSD	3.45	4.13	3
Workload Index HD	3.92	4.62	3.28
Fractal Dimension	2.68	2.66	2.6
CO2 Emissions	28432.58	28399.13	15446.12

An overview of the performance of the metrics for super high demand is shown in Table 39.

Table 39. Complexity Metrics Performance - MUAC (super high)

Metric	Actual	ATS	FRA
Dynamic Density	1.199	1.232	0.926
Workload Index SSD	4.59	5.19	3.89
Workload Index HD	5.2	5.8	4.25
Fractal Dimension	2.78	2.75	2.72
CO2 Emissions	49425.5	49412.81	29205.19

Table 40. Overall Results MUAC Airspace (Normal)

Variable	**MUAC-Actual-normal**	**MUAC-ATS-normal**	**MUAC-FRA-normal**
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	22.98	23.0	22.96
Total AC	3997	3992	3608
Time spent per AC [min]	19.74	21.44	20.08
Normalised Proximate Aircraft Pairs [%]	45.36	69.61	23.79
Along Track [%]	10.04	17.94	6.14
Crossing [%]	19.41	29.03	8.95
Opposite [%]	15.91	22.64	8.7
Traffic Phase Cruising [%]	51	53	45
Traffic Phase Descending [%]	2	1	13
Traffic Phase Climbing [%]	47	46	42
Mix of traffic altitudes	52	51	65
Traffic Evolution [FL]	5.956602545	6.104473209	4.591933654
Adjusted Density	1.43	1.5	1.4
Structural Index	0.66	0.68	0.33
Horizontal Interactions	0.65	0.68	0.36
Vertical Interactions	0.14	0.16	0.09
Speed Interactions	0.34	0.42	0.16
Complexity Score	1.138	1.257	0.609
Overall Penalty Score	0.0205071	0.06604129	0.041886998
SSD Workload Index	(4.027, 2.902, 2.201, 1.107)	(4.6478, 3.353, 2.932, 1.893)	(4.6709, 2.499, 1.9676, 1.19)
HD Workload Index	(4.553, 3.264, 2.45215, 1.242)	(5.3175, 3.740, 3.284, 2.07)	(5.10751, 2.7246, 2.121, 1.31)
Fractal Dimension	2.509347826	2.520217391	2.441014493
CO2 Emissions	25537.85738	25507.51865	13561.6702

Table 41. Overall Results MUAC Airspace (High)

Variable	MUAC-Actual-high	MUAC-ATS-high	MUAC-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	23.0	23.0	22.97
Total AC	6622	6445	5825
Time spent per AC [min]	18.77	20.28	18.12
Normalised Proximate Aircraft Pairs [%]	86.65	111.47	37.12
Along Track [%]	18.72	28.12	9.31
Crossing [%]	35.01	42.15	12.93
Opposite [%]	32.92	41.2	14.88
Traffic Phase Cruising [%]	55	58	46
Traffic Phase Descending [%]	4	4	16
Traffic Phase Climbing [%]	41	39	38
Mix of traffic altitudes	52	51	67
Traffic Evolution [FL]	5.597886374	5.633940472	4.520252269
Adjusted Density	1.04	1.05	1.09
Structural Index	0.88	0.95	0.6
Horizontal Interactions	0.52	0.53	0.38
Vertical Interactions	0.16	0.18	0.13
Speed Interactions	0.3	0.37	0.2
Complexity Score	0.982	1.084	0.715
Overall Penalty Score	0.041257538	0.097456408	0.058276003
SSD Workload Index	(5.530, 4.329, 3.78913, 2.243)	(6.4944, 4.90, 4.436, 2.91)	(6.6516, 3.5481, 3.0741, 1.753)
HD Workload Index	(6.229, 4.891, 4.294, 2.563)	(7.4173, 5.5271, 4.9, 3.20)	(7.331, 3.88, 3.32, 1.934)
Fractal Dimension	2.681413043	2.661086957	2.603333333
CO2 Emissions	28432.57744	28399.13227	15446.11854

Table 42. Overall Results MUAC Airspace (Super High)

Variable	MUAC-Actual-high	MUAC-ATS-high	MUAC-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	23.0	23.0	22.97
Total AC	8890	8413	7837
Time spent per AC [min]	18.66	20.14	18.12
Normalised Proximate Aircraft Pairs [%]	115.38	147.32	50.11
Along Track [%]	25.45	38.36	12.8
Crossing [%]	45.16	54.93	17.76
Opposite [%]	44.77	54.03	19.55
Traffic Phase Cruising [%]	56	57	46
Traffic Phase Descending [%]	4	4	16
Traffic Phase Climbing [%]	40	39	39
Mix of traffic altitudes	52	51	68
Traffic Evolution [FL]	5.600363242	5.624836374	4.525935973
Adjusted Density	1.14	1.14	1.21
Structural Index	1.0	1.0	0.7
Horizontal Interactions	0.61	0.6	0.49
Vertical Interactions	0.22	0.21	0.18
Speed Interactions	0.38	0.42	0.26
Complexity Score	1.199	1.232	0.926
Overall Penalty Score	0.057948835	0.130352483	0.082263983
SSD Workload Index	(7.0458, 5.8326, 4.99, 3.042)	(8.0175, 6.233, 5.6743, 3.587)	(8.442, 4.645, 4.05, 2.29)
HD Workload Index	(7.92, 6.57, 5.674, 3.471)	(9.118, 7.009, 6.358, 3.95)	(9.29, 5.0575, 4.345, 2.513)
Fractal Dimension	2.779782609	2.745398551	2.723985507
CO2 Emissions	49425.50434	49412.81202	29205.19302

3. CSE

An overview of the performance of the metrics for normal demand is shown in Table 43.

Table 43. Complexity Metrics Performance - CSE (normal)

Metric	Actual	ATS	FRA
Dynamic Density	2.405	2.812	1.111
Workload Index SSD	2.06	2.24	1.08
Workload Index HD	2.31	2.52	1.18
Fractal Dimension	2.77	2.76	2.72
CO2 Emissions	200059.38	200842	175263.34

An overview of the performance of the metrics for high demand is shown in Table 44.

Table 44. Complexity Metrics Performance - CSE (high)

Metric	Actual	ATS	FRA
Dynamic Density	3.083	3.297	2.095
Workload Index SSD	3.06	3.3	1.59
Workload Index HD	3.44	3.72	1.72
Fractal Dimension	2.82	2.8	2.77
CO2 Emissions	220944.96	221343.75	193996.19

An overview of the performance of the metrics for super high demand is shown in Table 45.

Table 45. Complexity Metrics Performance - CSE (super high)

Metric	Actual	ATS	FRA
Dynamic Density	3.557	3.784	2.883
Workload Index SSD	3.98	4.16	2.07
Workload Index HD	4.47	4.69	2.24
Fractal Dimension	2.84	2.81	2.8
CO2 Emissions	359727.02	359092.37	319967.85

Table 46. Overall Results CSE Airspace (Normal)

Variable	**CSE-Actual-normal**	**CSE-ATS-normal**	**CSE-FRA-normal**
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	9.0	9.0	8.98
Total AC	4424	4622	2629
Time spent per AC [min]	33.81	35.19	32.14
Normalised Proximate Aircraft Pairs [%]	40.75	53.14	11.82
Along Track [%]	7.3	12.3	2.22
Crossing [%]	20.1	25.33	6.04
Opposite [%]	13.35	15.51	3.56
Traffic Phase Cruising [%]	54	53	55
Traffic Phase Descending [%]	3	2	15
Traffic Phase Climbing [%]	43	45	30
Mix of traffic altitudes	52	52	59
Traffic Evolution [FL]	3.706315536	3.743475077	3.182482504
Adjusted Density	2.2	2.42	2.59
Structural Index	1.01	1.07	0.38
Horizontal Interactions	1.31	1.48	0.65
Vertical Interactions	0.29	0.34	0.16
Speed Interactions	0.81	1.0	0.3
Complexity Score	2.405	2.812	1.111
Overall Penalty Score	0.01696873	0.031185865	0.008480387
SSD Workload Index	(3.353, 2.81, 2.282, 1.192)	(3.6433, 2.940, 2.466, 1.3762)	(3.119, 1.288, 0.954, 0.573)
HD Workload Index	(3.860, 3.195, 2.545, 1.31)	(4.203, 3.31, 2.753, 1.525)	(3.485, 1.39, 1.00, 0.615)
Fractal Dimension	2.771018519	2.758333333	2.716944444
CO2 Emissions	200059.3757	200842.0028	175263.3414

Table 47. Overall Results CSE Airspace (High)

Variable	CSE-Actual-high	CSE-ATS-high	CSE-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	9.0	9.0	8.98
Total AC	6714	7001	3995
Time spent per AC [min]	34.36	35.49	32.71
Normalised Proximate Aircraft Pairs [%]	65.24	80.47	17.05
Along Track [%]	13.22	18.73	3.52
Crossing [%]	31.02	38.75	8.23
Opposite [%]	21.0	22.99	5.3
Traffic Phase Cruising [%]	55	52	55
Traffic Phase Descending [%]	3	2	15
Traffic Phase Climbing [%]	43	45	30
Mix of traffic altitudes	52	52	59
Traffic Evolution [FL]	3.755940644	3.818784776	3.106752351
Adjusted Density	2.69	2.71	3.15
Structural Index	1.07	1.14	0.61
Horizontal Interactions	1.66	1.71	1.22
Vertical Interactions	0.39	0.42	0.27
Speed Interactions	1.04	1.17	0.61
Complexity Score	3.083	3.297	2.095
Overall Penalty Score	0.030028425	0.050282717	0.015368544
SSD Workload Index	(4.759, 4.177, 3.37, 1.83)	(5.163, 4.281, 3.620, 2.10)	(4.643, 1.99, 1.314, 0.829)
HD Workload Index	(5.499, 4.723, 3.77, 2.0252)	(5.96, 4.83, 4.066, 2.33)	(5.206, 2.131, 1.410, 0.878)
Fractal Dimension	2.81537037	2.797037037	2.77037037
CO2 Emissions	220944.9581	221343.7513	193996.1943

Table 48. Overall Results CSE Airspace (Super High)

Variable	CSE-Actual-high	CSE-ATS-high	CSE-FRA-high
Day	weekday (Wednesday,6th)	weekday (Wednesday,6th)	weekday (Wednesday,6th)
Opening Time	9.0	9.0	9.0
Total AC	8994	9006	5361
Time spent per AC [min]	34.43	35.66	32.38
Normalised Proximate Aircraft Pairs [%]	88.81	104.85	23.67
Along Track [%]	18.06	25.93	4.3
Crossing [%]	41.82	49.7	11.08
Opposite [%]	28.93	29.22	8.29
Traffic Phase Cruising [%]	54	53	54
Traffic Phase Descending [%]	3	2	15
Traffic Phase Climbing [%]	43	45	31
Mix of traffic altitudes	52	52	60
Traffic Evolution [FL]	3.772286204	3.745396795	3.132514427
Adjusted Density	3.02	3.04	3.58
Structural Index	1.1	1.18	0.72
Horizontal Interactions	1.9	1.96	1.69
Vertical Interactions	0.45	0.49	0.35
Speed Interactions	1.2	1.33	0.84
Complexity Score	3.557	3.784	2.883
Overall Penalty Score	0.041171137	0.06943077	0.021389378
SSD Workload Index	(6.055, 5.352, 4.445, 2.430)	(6.341, 5.41, 4.52, 2.721)	(5.900, 2.547, 1.771, 1.09)
HD Workload Index	(7.024, 6.03, 4.951, 2.671)	(7.35, 6.125, 5.076, 3.016)	(6.627, 2.723, 1.87, 1.168)
Fractal Dimension	2.843796296	2.813148148	2.800740741
CO2 Emissions	359727.0183	359092.3705	319967.8524

B. Appendix B: Literature Study

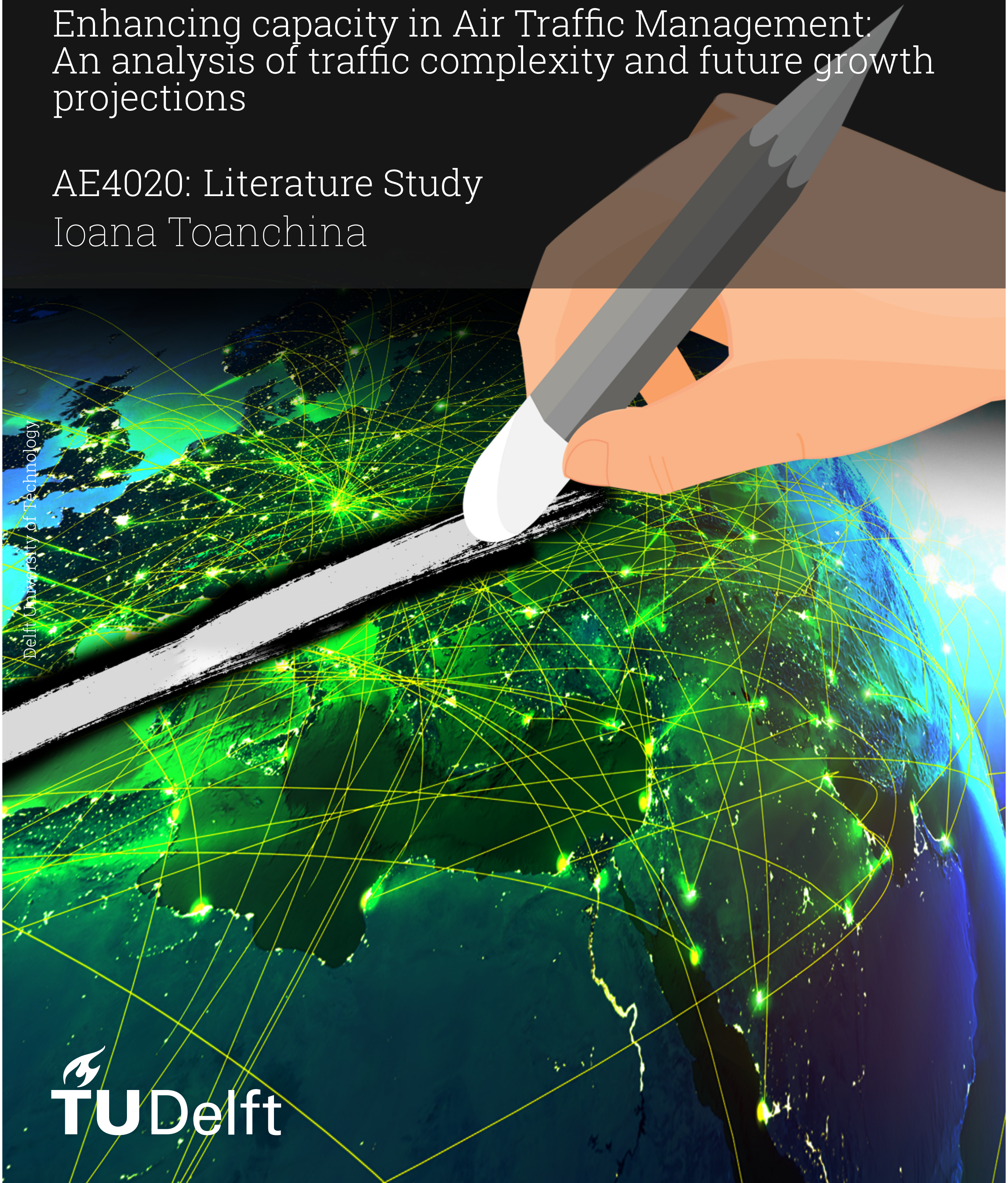
Already Graded

Literature Study

Enhancing capacity in Air Traffic Management: An analysis of traffic complexity and future growth projections

AE4020: Literature Study

Ioana Toanchina



Delft University of Technology

Literature Study

Enhancing capacity in Air Traffic Management: An analysis of traffic complexity and future growth projections

by

Ioana Toanchina

Student Name	Student Number
Ioana TOANCHINA	5630800

Instructors: Prof.dr.ir J.M. Hoekstra, Dr.ir J. Ellerbroek
Profile: Sustainable Air Transport
Track: Control and Operations
Faculty: Faculty of Aerospace Engineering, Delft

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TUDelft

Preface

After a significant decrease in air traffic due to the COVID-19 pandemic, the aviation industry is starting to see signs of recovery with an increasing demand for flights. In 2019, the aviation industry set a record for the highest number of daily flights, and it is expected that this record will be broken in the upcoming years. However, to accommodate this surge in air traffic, it is essential to optimize the capacity of the airspace and implement effective airspace management strategies. This will ensure that the airspace is well-equipped to handle the projected increase in flights, and that the Air Traffic Management, ATM, system can continue to operate safely and efficiently.

The free routing approach is an ATM method which allows the airspace users to freely plan their flights by choosing desired routes between predefined points. In most of the European airspace, this approach is often used in the en-route environment. Free Route Airspace, abbreviated FRA, offers a range of significant benefits, including enhancing the capacity within sectors while reducing the fuel consumption by shortening the trajectories. This not only saves money for airlines but also minimizes the environmental impact of air industry. However, the freedom of choosing the routes affects the Air Traffic Management and increase the air traffic complexity.

As such, it is important to conduct research on the effectiveness of the free routing method, especially on its performance from the point of view of the traffic complexity. By doing so, evidence-based policies and strategies can be developed to optimize the airspace management and to ensure the sustainability of the aviation industry.

Moreover, to fully comprehend the effect of free routing on sector capacity, it is highly important to analyze how this approach impacts the capacity of the airspace across different traffic complexity metrics. Therefore, this report presents an in-depth literature review, examining different research papers in which air traffic complexity is assessed in relation to the implementation of FRA. By exploring this topic, the report aims to contribute to the ongoing discussions on optimizing airspace management and enhancing the efficiency of air transportation.

Ioana Toanchina
Delft, June 2023

Summary

The current air traffic over Europe already generates a huge amount of workload for the controller. To accommodate all the demand, the airspace is divided into elementary sectors in which the air traffic is organized in air flows. This results in ensuring the flight safety, as well as the network's capacity. However, in the upcoming years, the demand in aviation is predicted to overtake the record figures of pre-pandemic period. A feasible solution of enhancing capacity over sectors without exposing the level of safety to a risk may be the implementation of Free Route Airspace.

Thus, this paper presents a comprehensive literature review of optimizing the capacity of the airspace for future growth scenarios based on the impact of Free Route Airspace implementation on different traffic complexity metrics. Being one of the most complex airspace areas over Europe, a briefly description of MUAC has been done in this report. MUAC is strategically positioned over the busiest airports from Europe connecting the traffic from Atlantic to the east of Europe and the other way around. Operating Free Route Airspace technology within this airspace area, MUAC still face the challenge of demand exceeding capacity phenomenon. Therefore, an analysis of different complexity metrics needs to be conducted in order to reveal the optimal strategies in order to accommodate in an safe manner whole the future traffic growth.

Setting up the two main objectives, Chapter 2 starts with a close up of the aviation future demand and how this may affect the capacity at a network level. The benefits and drawbacks of two operational modes are described in Chapter 3. The implementation of Free Route Airspace addresses some of ATS routing limitations having also a better impact on the environment. However, the freely planning concept introduced once with this implementation affect the complexity in the airspace. As a consequence, the workload of an air traffic controller increases. In order to accommodate the traffic with a high level of complexity, the air traffic controllers needs to adopt the most efficient strategy. The link between air traffic controller's workload and the level of complexity present in the airspace is detailed in Chapter 4. In this chapter, factor and metrics of complexity are described. Finally, the report end with a section of conclusions, Chapter 5, and also with the future research plan of this topic, Chapter 6.

Contents

List of Figures

Nomenclature

Abbreviations

Abbreviation	Definition
ACC	Area Control Centre
AIP	Aeronautical Information Publication
AL	Alerting Service
ANSP	Air Navigation Service Provider
AOR	Area of Responsibility
APP	Approach Control
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Service
CHMI	Collaboration Human Machine Interface
COCA	Complexity and Capacity Project
CNS	Communications, Navigation and Surveillance
CTA	Control Area
CTR	Control Zone
DFS	Deutsche Flugsicherung
ECI	Economic Complexity Index
FAB	Functional Airspace Block
FABEC	Functional Airspace Block Europe Central
FBZ	Forbidden Beam Zone
FIR	Flight Information Region
FIS	Flight Information Service
FL	Flight Level
FRA	Free Route Airspace
FRAP	Free Route Airspace Project
IC	Interval Complexity
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
LFV	Luftfartsverket
LVNL	Luchtverkeersleiding Nederland
NEFRA	Northern Europe Free Route Airspace
NM	Nautical Miles
RNAV	Area Navigation
SES	Single European Sky
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure Route
SSD	Solution Space Diagram
STAR	Standard Arrival Route
SUA	Special Use Airspace
TMA	Terminal Area
TWR	Tower Control
UAC	Upper Area Control Centre
UTA	Upper Control Area
WHO	World Health Organization
WJHTC	FAA William J. Hughes Technical Center

1 Introduction

This report presents a thorough investigation on the capacity of airspace and a comprehensive evaluation of the free routing approach viewed from different perspectives of air traffic complexity metrics. Based on a comprehensive analysis of different research papers, this literature review aims to dissect the impact of the free routing implementation on traffic complexity and to propose the most efficient approach that enhances capacity, while maintaining an exceptionally high level of safety.

Hereby, the introduction section guides the reader into the research topic followed by a presentation of the report's objectives and research questions. Finally, this part ends with an overview of the structure of the report creating a clear framework for understanding its key findings.

1.1. Scope of the research

Air transportation has rapidly developed over the past century, transforming the air into a fast way to travel, to connect people over the world, and also to conduct business. From the first commercial flight in 1914, the air travel has evolved from a luxury reserved for the wealthy to a convenient and affordable mode of transportation accessible to millions of people worldwide. Nowadays, it has become an indispensable part of modern society with large number of passengers and tons of cargo being transported over the world every day. Moreover, the liberalization of air transport policies and the growth of low-cost carriers have further popularized air travel, making it available to more people than ever before.

However, this industry is a dynamic and constantly expanding system, closely tied to consumer behavior, economic cycles, and other external factors. According to [43], the attribute of "volatility" is inherent to this industry, making it a continuously developing and innovative field. From seasonal fluctuations to global issues, the airline companies and other air stakeholders face a wide range of challenges that can impact their performance and profitability.

In particular, the COVID-19 pandemic exponentially altered the air traffic over the world. After a record year in 2019, the global health crisis caused a sharp and unexpected decrease in traffic flow, particularly with regard to passenger flights. In 2019 the air travel demand hit the highest number of flights around the European airspace, with more than 37,000 flights over the course of the day. The record was established, during a summer day, on 28th of June.[35] Few months later, in March 2020, the World Health Organisation, WHO, declared Europe the epicentre of the pandemic, which obliged most of the countries worldwide to adopt national lockdown procedure. [61] Together with the safety measurements that were taken in place, the aviation industry has experienced unprecedented changes. Thus, the sharp decline in number of daily flights was caused by the outbreak of the pandemic which forced countries to close their borders and impose travel restrictions.

In the response of the COVID-19 pandemic, statistical tests began forecasting the recovery of the air traffic. The European Organisation, EUROCONTROL, responsible for predicting the traffic around Europe, developed different scenarios to create a more accurate situation of the future traffic growth with the goal of anchoring the recovery to 2019 levels. In present, three years after the beginning of the pandemic, the aviation industry is facing new challenges by experiencing a rapid recovery. Predictions indicate that the number of flights will increase and surpass the figures seen in 2019 which can produce negative consequences, including congestions in parts of the airspace. As a result, it is important that ATM systems are prepared to handle this demand and adopt the most productive strategies to ensure optimal performance and efficiency in the air.

In 2004, on the en-route environment, EUROCONTROL came up with the concept of Free Route Airspace, FRA. The aim of this concept is to increase the flexibility of airspace management by allowing the aircraft to choose direct routes between predefined entry and exit points of sectors. Since then, many countries in and outside of Europe implemented this strategy as a solution to increase airspace capacity and to improve the overall performance of the Air Traffic Management systems. This approach offers several notable benefits, such as decreasing CO_2 emissions or reducing the fuel consumption, both while shortening the flight time. However, FRA poses a number of challenges and issues. The freedom of choosing the routes affects the operational environment by creating ”invisible intersection points” which might generate more complexity of the traffic. This key factor may increase the air traffic controller workload and develop different potential risks on the safety levels.

Therefore, an attentive close-up of the impact of the free routing concept on the traffic complexity is necessary to be analyzed. The free routing approach seems to be a viable solution for enhancing the capacity for the future traffic growth scenarios. However, it could create more complexity in the airspace. In conclusion, this research paper provides an analysis of the FRA implementation on different traffic complexity metrics in order to develop effective strategies for optimizing airspace capacity and enhancing the overall performance of the ATM.

1.2. Research framework

In order to establish a clear direction for this report, it is necessary to define the research framework. The first step of this process is to identify the research objective, which represents the foundation for all subsequent analysis and conclusions. Thus, the main objective of this study is:

Based on the impact of Free Route Airspace implementation on different traffic complexity metrics, optimize the capacity of the airspace for future traffic growth scenarios.

In order to accomplish the research objective outlined above, a main research question needs to be addressed. Moreover, in order to have a detailed and widespread answer to the question, there are some sub-questions that should be answered.

- *How does the implementation of Free Route Airspace, FRA, impact sector capacity when assessed using different traffic complexity metrics?*
  - What are the main factors that influence the sector capacity?
  - What are the most used traffic complexity metrics in measuring the sector capacity?
  - How does the implementation of FRA affect the traffic complexity?

Additionally, on a second level of analysis, another research question with its sub-questions need to be answered.

- *How does the implementation of Free Route Airspace, FRA, contribute to the sustainability of air transport?*
  - What are the environmental factors affected by FRA?
  - To what extend can the implementation of FRA contribute to enhancing the sector capacity, while maintaining a low level environmental impact?

1.3. Structure of the literature review

To tackle the research questions outlined in Section 1.2, focusing on the scope of the research topic, this report is structured as follows. Chapter 2 provides background information to the problem. First section of the chapter, Section 2.1, starts with a short introduction in aviation demand highlighting the current situation for Europe. After a briefly presentation about the structure of the airspace and the main characteristics of the network presented in Section 2.2, Section 2.3 defines the sector capacity and explains how this can be measured. All of these factors will be included later on in the experimental phase, namely in the definition of the independent variables. The chapter concludes with an overview of Maastricht Upper Area Control airspace in Section 2.4.

Further, Chapter 3 focuses on the two operational methods implemented in ATM, namely Free Route Airspace and Air Traffic Service, ATS, routing concept. Section 3.1 is starting with the definition of the traditional approach of the airspace management, namely the aircraft flying on ATS routes. The section is followed by mentioning the most congested intersections and explaining the benefits and drawbacks of this method from different perspectives, such as operational or environment aspects. In Section 3.2 the concept of free routing is described. The implementation process and its particularities are also highlighted in this section. The upsides and downsides of this approach are briefly explained. The chapter concludes with displaying the current situation for MUAC airspace regarding the implementation of these two ATM methods.

Chapter 4 introduces the notion of traffic complexity and how this is used in the specialized literature. The chapter starts with Section 4.1 where a general definition of the complexity used in different fields is presented. A close-up look for this topic in the Air Traffic Control environment is done in Section 4.2. The chapter continues with presenting the factors that define the air traffic complexity, in Section 4.3. In the end of the chapter, Section 4.4 shows different metrics that are used in the aviation research to estimate the complexity of a sector while Section 4.5 explored the complex character of the airspace under MUAC responsibility. A summary of the chapter is allocated for each part of the report.

Finally, the report has a dedicated part for presenting the conclusions. Chapter 5 discusses the main findings and conclusions. Moreover, Chapter 6 highlights the future work that will be done and its approach for this research study.

2 Background information

As the aviation industry continues to expand, the limited airspace becomes a significant factor to consider. With the demand for the air travel forecasted to increase in the upcoming years, understanding the market demand and the structure of the airspace plays an essential role in targeting the scope of this research.

Thus, this chapter explores the trend of the aviation demand and the main particularities of the airspace. Additionally, it emphasizes how the capacity of the airspace can be defined and how this can be measured within sectors. Divided into four sections, Section 2.1 explains the demand in aviation with a focus of future growth scenarios, while Section 2.2 presents the characteristics of airspace with a close-up view of European area. Finally, Section 2.3 covers the topic of airspace capacity and Section 2.4 shows an overview of the most complex airspace in Europe, Maastricht Upper Area Control airspace. Section 2.5 represents a summary of the chapter.

2.1. Demand in aviation

Demand is a widely studied topic across different fields. For example, in economics, demand is defined as the amount of products or services that a consumer is willing and able to purchase [85], while in marketing it refers to the need for a particular product among a specific target audience. [42] In the domain of energy management, the amount of power needed to meet the electrical needs of consumers at a given time is used to express the demand. [11] Nevertheless, in context of transportation, the definition of demand can be found as the amount of passengers or goods that require transportation service. Depending on the field, in aviation, demand can be defined as the number of passengers or goods transported or the number of aircraft movements in a specific sector or region. [24] Despite the variations in definitions across different areas of research, the fundamental common characteristic of demand is the relationship between consumers and products. Based on the quality of the product or the need of the consumer, this relationship creates the demand.

Over time, the aviation industry has grown significantly in popularity as a mode of transportation for both passengers and goods. With affordable prices and accessibility, aviation has become a convenient option for a wide range of social classes. As a result, the demand for air travel has been on the rise in recent years. The increase in demand can be attributed to a combination of technological, economical and other external factors. Technologically, the aviation industry has seen advancements in aircraft design and performance, resulting in more spacious and faster aircraft that can carry larger volumes of passengers and cargo, while economic factors such as rising incomes or decreased airfares have made air travel more available. [77] highlights in the research paper that demand is closely related to economic factors by concluding that an increase in income per capita and a decrease in ticket prices have a positive impact on the demand.

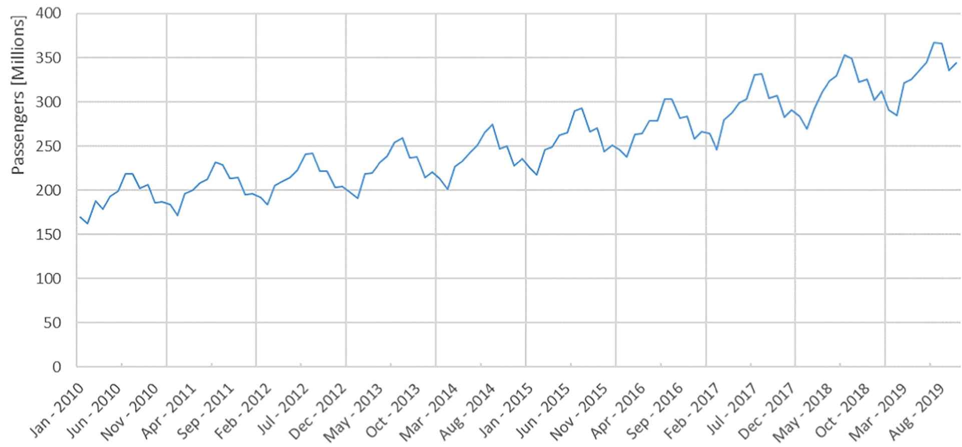


Figure 2.1: Global passenger volume growth trend 2010-2019 [47]

On the other hand, the demand in aviation is strongly correlated with seasons. For instance, in [47] a statistical regression model based on historical seasonal trends in the period January 2010 - October 2019 is applied, thus designing the air traffic scenarios for the period of 2020. According to Figure 2.1, the research paper highlights how the volume of passengers traveling by air has a global upward trend and exhibits a seasonal effect.

Demand in aviation is affected by the external factors, and the aviation industry itself is highly dependent on demand and its behavior. Thus, numerous studies have focused on developing forecasting models for future demand in order to find and use the most accurate forecasting tool.

For example, a study carried out in 2016 aimed to forecast the future growth in Flight Information Region, FIR, of Singapore. According to the findings presented in Figure 2.2, the estimated traffic in 2030 exceeds the one from the reference year, 2015, with at least two times. [68] Another study has forecasted the same trend of the traffic. In Turkey it was predicted that in the next decade there will be a continuous increase in demand. [65] Both studies could not anticipate the pandemic of COVID-19 and its impact around the aviation world.

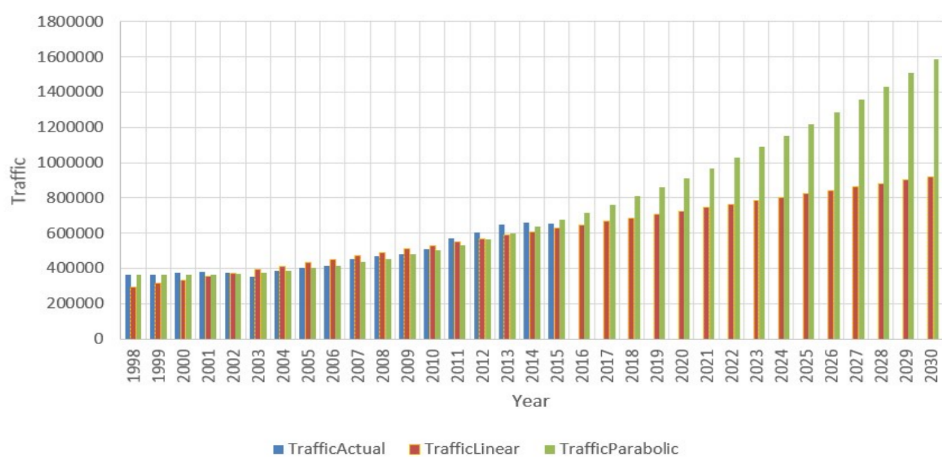


Figure 2.2: Singapore air traffic forecast [68]

However, more recent research studies are concluded with similar findings of future growth of air traffic even when they take the period of the coronavirus pandemic into consideration. On the other hand, by having as a reference the record of flights of 2019, most of the studies are developing the post-pandemic recovery forecast. For example, [75] analyzes the correlation between economic shocks and temporal recovery of the global air transport industry. Their results shows that in approximately 2.5 years from the coronavirus period world passengers and freight demand will reach the levels seen before the COVID-19 pandemic. A similar outcome was observed in a study conducted on the air transport recovery in Africa, where it is predicted that the air traffic will recover within 30 months from their reference year. [86]

Around Europe, the main organization responsible for forecasting is the European Organisation for the Safety of Air Navigation, EUROCONTROL. STATFOR, the Statistics and Forecast Service of EUROCONTROL, is in charge of providing regular updates and forecasts to help aviation stakeholders planning and monitoring the air traffic management system. The organization has developed three distinct forecast time horizons to calculate the total number of flights. [49]

Moreover, STATFOR outlines three distinct scenarios based on the global health crisis period. While the High scenario assumes that the vaccination campaign continues both within Europe and globally, with reliable vaccines that remain effective, the Baseline scenario has similar characteristics but at a slower rate. On the other hand, the Low scenario considers the impact of various downside risks, such as slow or patchy vaccination rates. [29]

Using an AI machine learning approach, it is expected that in 2025 the European airspace reaches 2019 flight levels, as can be seen in Figure 2.3. Further analysis of a short-term period forecast, specifically the week of 12 to 18 April 2023, reveals that flights have already reached approximately 90% of their 2019 levels. The results are presented in Figure 2.4.

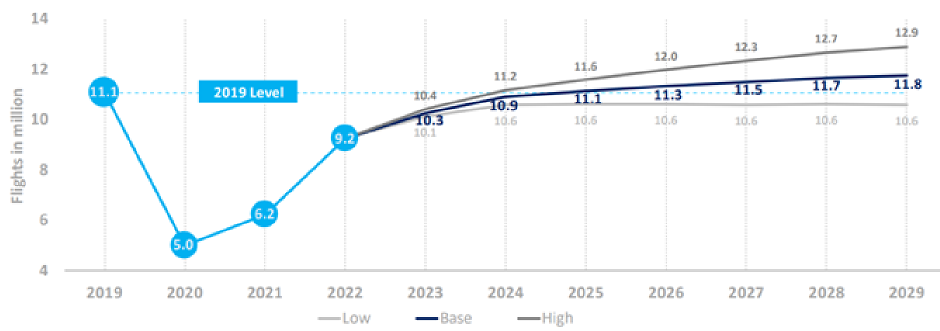


Figure 2.3: Traffic Scenarios around Europe for medium-term period forecast [30]

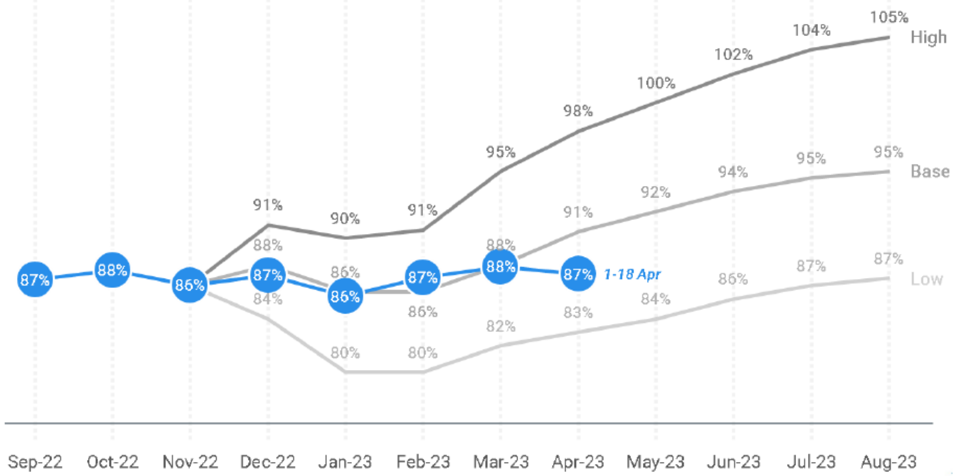


Figure 2.4: Traffic Scenarios around Europe for short-term period forecast [28]

This indicates that if the air traffic of 2019 is achieved in the near future, and no other global crises occur, the growth in air traffic will surpass the previous levels. As a result, there will be a need for a close-up analysis of the airspace capacity to manage the increased traffic by optimizing the workload of the aviation employees.

2.2. Airspace structure

Section 2.1 highlights the potential growth in air traffic, which will overtake the record of flights from 2019 in the upcoming years. Now, the question to ask is, are the physical conditions able to handle so much traffic? To answer this question it is important to understand the potential physical constraints that may hinder the expected growth in air traffic. In this case, this section delves into the configuration and management of the airspace, particularly focusing on the European airspace.

By its definition, a portion of the atmosphere subordinated by a country above its territory represents an airspace. [4] The International Civil Aviation Organisation, ICAO, who is responsible for promoting the safe and orderly development of civil aviation around the world, proposed to sub-divide the airspace of the world into nine ICAO air navigation regions, which are shown in the map displayed in Figure 2.5. By breaking down the world's airspace into these regional segments, the ICAO is able to promote cooperation and coordination among member states better, while also developing and implementing international standards and recommended practices for aviation safety, air navigation, security, and environmental protection. [50]

Among all nine ICAO air navigation regions, EUR is the busiest airspace in the world with an average of 30,000 flights on a typical day. [23] Moreover, according to [37], this region encompasses 56 states that are responsible for managing and providing services, making the airspace structure in this region highly complex. Given the immense volume of air traffic, ensuring safety and efficiency in the EUR airspace is a top priority. In this case the focus of this section will be on the airspace structure of the EUR ICAO air navigation region.

However, within EUR region, the largest division of airspace is called Flight Information Region, FIR. Every portion of the air is assigned to a FIR. While smaller countries typically have only one FIR, larger countries, like Italy or Germany, have multiple FIRs. To distinguish the FIRs, ICAO implemented a four letter designator for each area, where the first two letters represent the country code. The names of the FIRs can be seen in Figure 2.5.

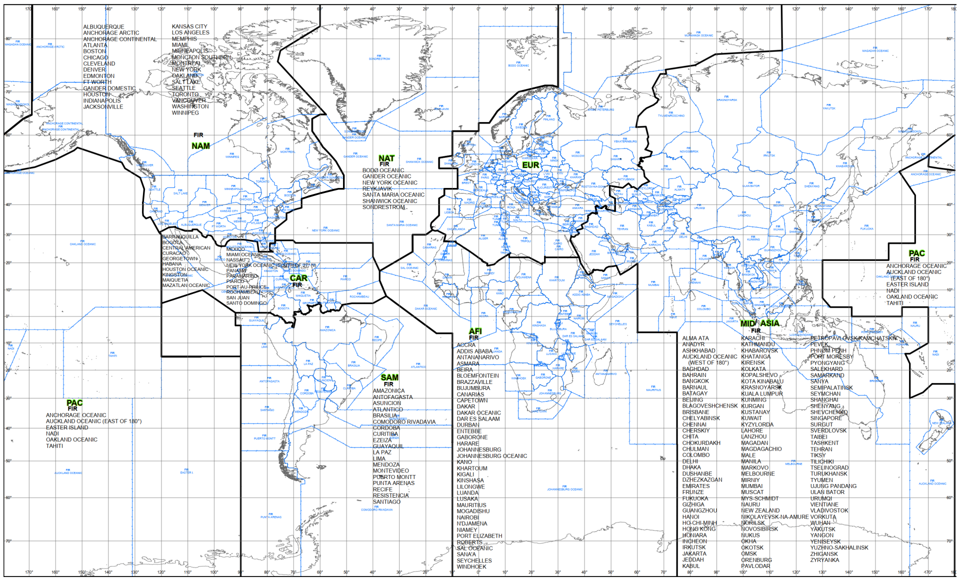


Figure 2.5: ICAO air navigation regions [80]

Moreover, the number of FIRs dedicated to an area can vary depending on the altitudes. As an example, the French airspace is divided into five FIRs below 19,500 ft which is correlated to FL195, and one large FIR above FL195. [64] Further, depending on function, size or classification, the airspace within a FIR is divided in small areas.

These areas can be controlled airspace or uncontrolled airspace. The controlled and uncontrolled areas define what kind of level of Air Traffic Services, ATS, can be expected within flying in these zones. In both areas, aircraft get Flight Information Service, FIS, and Alerting Service, AL. However, the distinction between these two types of airspace lies in the procedures governing aircraft entry and separation. In controlled airspace, pilots need to obtain a clearance from Air Traffic Control, ATC, to enter the space. On the other hand, in uncontrolled airspace, aircraft must rely on self-separation procedures to maintain a safe distance from one another. Pilots are responsible for actively monitoring their surroundings. [60]

For a better visualization, Figure 2.6 shows the airspace organisation. As can be observed, around the airport, labeled with star symbol, the area is called Control Zone, CTR. Here, the Tower Control, TWR, is in charge of operations. Surrounding the CTR is the Terminal Area, TMA, which serves as an intermediate airspace layer. The APP, Approach Control, responsible for TMA, accommodates aircraft transitioning between the airport and higher-altitude airspace. Between CTR and TMA, the uncontrolled airspace is found. Further, above the TMA lies the Control Area, CTA, and above CTA is UTA, the Upper Area. ACC, or Area Control Centre, respectively UAC, Upper Area Control Centre, assume responsibility for aircraft control in these two parts.

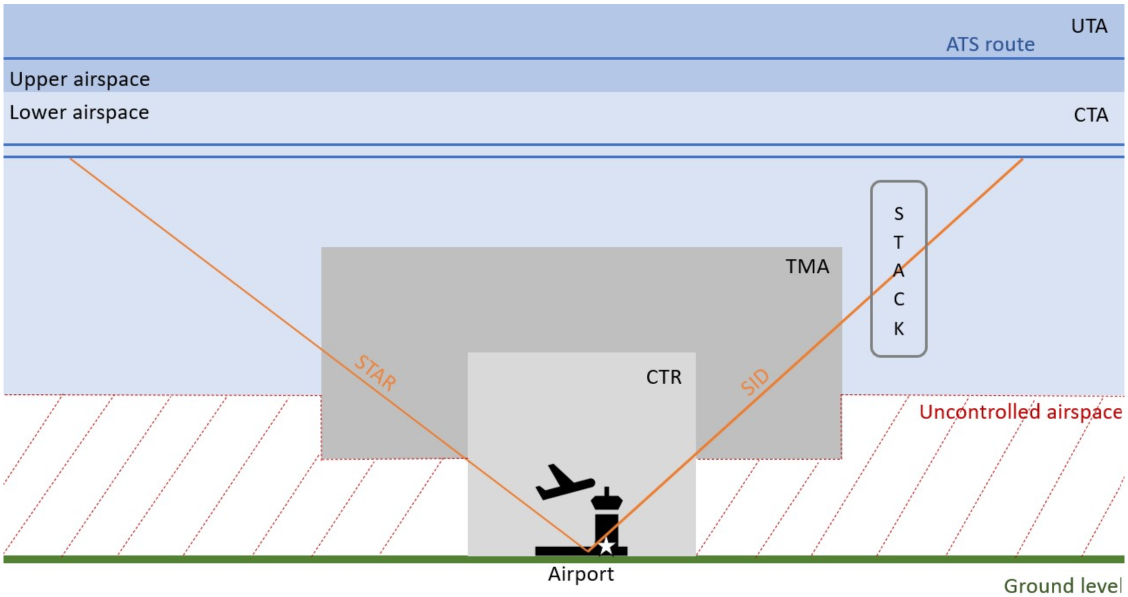


Figure 2.6: Airspace organisation

Within the airspace organisation, it can be found the ATS routes, the highways in the sky. However, in the last decade the possibility of free flying was integrated in the ATM system. Thus, apart from the ATS routes, the aircraft can freely choose between two predefined points to fly. These two concepts will be explained later in Chapter 3. Moreover, in TMA a Stack area is present. When necessary, the ATC delays aircraft and let them fly a holding pattern. This procedure can be helpful when there is a congestion in the airspace. Moreover, the departures and arrivals are followed by designated routes. For aircraft ready to land, they transition from ATS route to the airport by following a Standard Terminal Arrival Route, STAR. Conversely, departing aircraft initially follow a Standard Departure Route, SID, from the airport until they join their desired ATS route.

Apart from controlled and uncontrolled airspace, other area that can influence the complexity of the airspace is the Special Use Airspace, SUA. SUA is dedicated in most of the cases to all the military zones, to the airspace above royal palaces, or even to the area of an airshow. Depending on the attribution of the area, this airspace can be active 24 hours a day, or for several hours during a week or year. Pilots can find the information of this zone in Notice To Airmen, NOTAM, which represents a notice containing information concerning the establishment, condition or change in any aeronautical facility. [81]

Also, SUA can be divided in prohibited, restricted, and danger areas. In prohibited areas, the flights of aircraft is prohibited, while in restricted areas they are restricted in accordance with certain specified conditions. Nevertheless, danger areas are airspace in which activities dangerous to the flights of aircraft may exist at specific times. [62] The existence of numerous SUA areas in EUR region adds an additional level of complexity to the already intricate airspace landscape. By looking in Figure 2.7 it can be said that the airspace around Europe would transform into a multifaceted environment, blending military operations with the navigation of commercial flights. The SUA is shown by the red color. For commercial flights operating in this military-dominated airspace, the complexity escalates. Pilots and air traffic controllers face the task of meticulously planning routes that avoid or traverse these activated special use airspace areas, while ensuring the safety and efficiency of civilian operations.

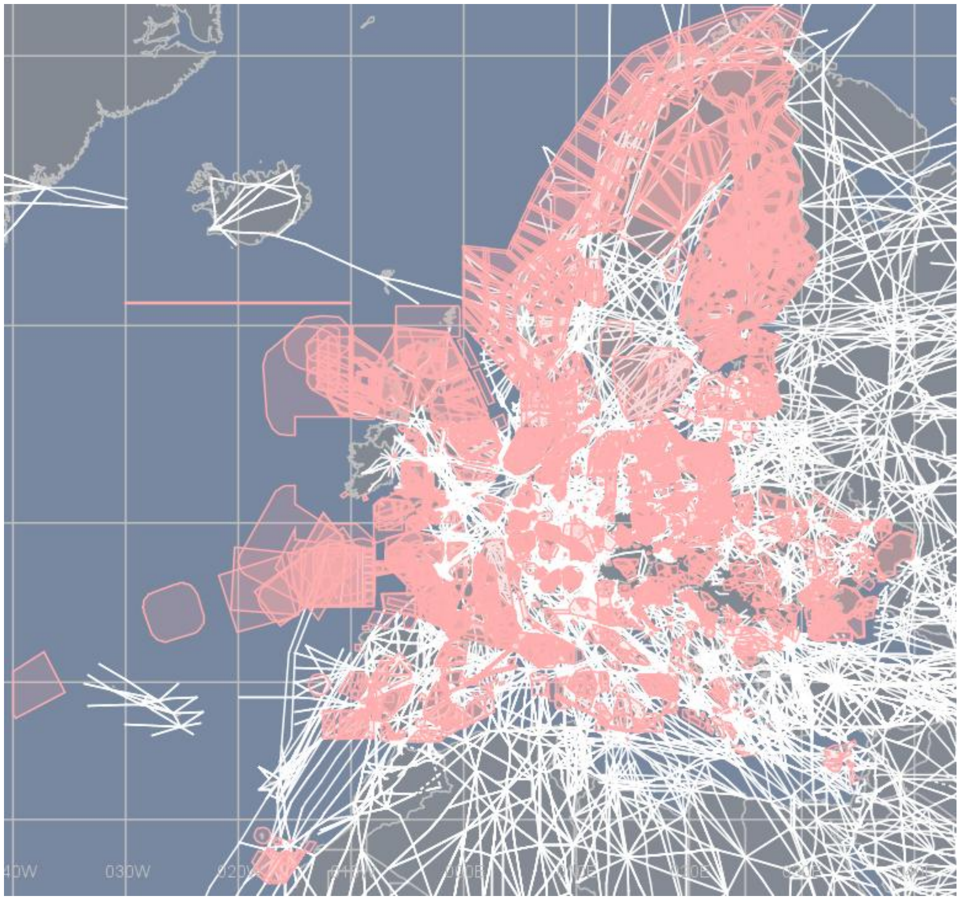


Figure 2.7: Special Use Airspace over Europe. Generated by Collaboration Human Machine Interface, CHMI

Considering all the elements mentioned above, the airspace transforms into an intricate and interconnected system that demands careful operation. With the implementation of appropriate strategies and Air Traffic Management (ATM) methods, the airspace can adeptly manage heightened demand, while ensuring efficiency and safety.

2.3. Sector capacity

The primary aim of Air Traffic Control is to ensure aircraft safety and maintain an efficient flow of air traffic. However, a single team of controllers cannot handle a high traffic volume within a big airspace. Hence, the concept of sectorisation was integrated in the ATC system. Sectorisation is the process of allowing the workload to be distributed among multiple teams of controllers. [82] The configuration of the sectors may vary during a day. For example, they can be split into more sectors when the traffic load increases, or merged when the traffic load decreases. Hence, the configuration of sectors is well linked to the capacity concept that needs to be applied in that airspace.

The concept of capacity is well-known in air transportation, especially in the en-route environment. By its definition, capacity represents the system's ability to accommodate a maximum number of aircraft within a defined timeframe. [79] According to [36], there are three types of capacity. The first type is declared capacity. Declared capacity represents the maximum number of aircraft that the sector can typically accommodate within a given hour. In certain circumstances such as bad weather or military activity, the actual number of aircraft permitted in the sector per hour may be lower than the declared capacity. This reduced capacity, is known as the deployed capacity, the second type. Finally, in order to meet future growth demands and address current capacity limitations, Air Navigation Service Providers, ANSPs, are tasked with planning and implementing additional capacity within the airspace.

Thus, planned capacity is the last type of capacity mentioned in their report.

However, capacity encompasses more than just a number of aircraft within an airspace at a given period of time. It considers several influential factors that contribute to, such as airspace design, ATC procedures, navigation capabilities or communication systems. Extensive research in recent years has thoroughly examined the impact of various factors on capacity within sectors. Most of the studies correlate the capacity with one big aspect, namely ATC workload. For example, [54] concluded their study by highlighting that the ATC workload represents a limiting factor on capacity. Also, using a Reorganized ATC Mathematical Simulator, RAMS, model, [1] discovered a strong connection between capacity and the workload of the Air Traffic Controller.

Another external factor that can contribute to express the capacity within the sector is the airspace configuration. In [41] is presented a forecast of airspace capacity and how the airspace can be design based on artificial intelligence models. It is found that the capacity of the traffic handled by an Air Traffic Controller can be determined by the sector configuration. Also the severe weather conditions might create an impact in estimating the capacity. [83] concludes their study by mentioning that the weather can affect the capacity of a sector.

More over, the concept of capacity is interconnected with the safety operational environment. In order to allocate the capacity within a sector, the minimum separation between aircraft needs to be taken into consideration. Aircraft flying in the en-route environment, must be separated by 1000 ft vertically unless they are separated horizontally. The horizontal separation standard for aircraft operating at the same altitude is 5 nautical miles, NM. [46] Within the airspace, each aircraft is enveloped by an invisible cylinder known as the standard minimum separation. This critical space ensures that no two aircraft can occupy it simultaneously to avoid any potential loss of separation. This is displayed in Figure 2.8.

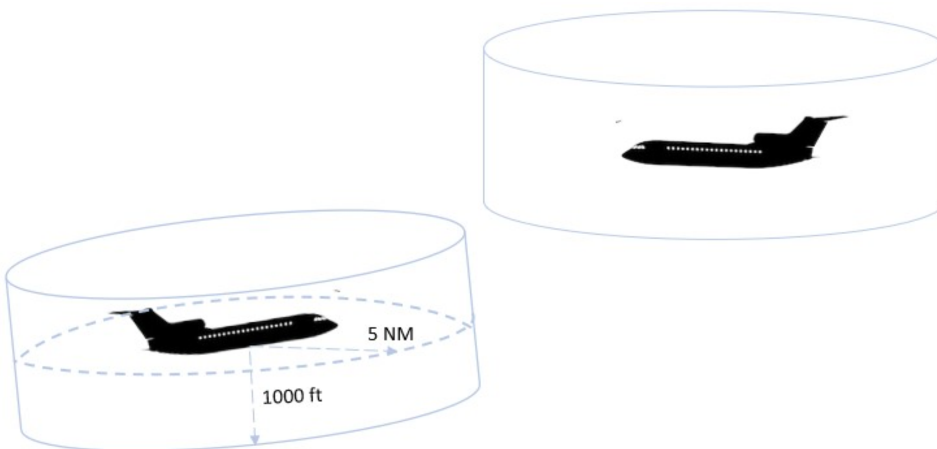


Figure 2.8: Standard en route separation minima

In conclusion, the capacity analysis of a sector takes into account various critical factors. These elements collectively contribute to the complexity of the airspace, creating a dynamic and intricate system. Balancing the demand and capacity within this complex environment becomes paramount, requiring thorough analysis and strategic planning. Thus, to meet the increasing future demand, apart from knowing the physical constraints of the environment, it is essential to examine the existing methods of aircraft operation within this environment. Additionally, conducting a comprehensive assessment of the traffic complexity within the sector assumes significant importance. These important topics will be explored in the forthcoming chapters.

2.4. Overview of MUAC airspace

Maastricht Upper Area Control, MUAC, is responsible for managing the upper airspace, ranging from 24,500 ft, which corresponds to FL245, to 66,000 ft, which is FL600. The airspace is over Belgium, the Netherlands, Luxembourg, north-west Germany, and the adjoining areas of the North Sea. This area represents one of Europe's busiest and most complex airspace.[9] Thus, a close-up of MUAC airspace and its sectors is highlighted in this section.

The boundaries of the MUAC airspace are well-defined, encompassing the upper airspace above FL245 over Belgium, Netherlands, Luxembourg, and a portion of Germany. Additionally, MUAC is responsible for managing the air traffic in the adjoining areas of the North Sea. [39] Conversely, the lower airspace above these territories falls under the jurisdiction of Belgium's National Services, called Blegocontrol, the Netherlands' National Services, LVNL, and Germany's National Services, DFS. [63], [19], [6] In terms of size, MUAC airspace covers an extensive surface area equivalent to 76,000 square NM and in terms of flights, this airspace handles an average of 1.9 million flights annually. [26] Moreover, the area of responsibility, AOR, is surrounded by major airports, such as Amsterdam, Brussels, Copenhagen, Düsseldorf, Frankfurt, London, and Paris. The geographical position of the MUAC airspace is displayed in Figure 2.9.

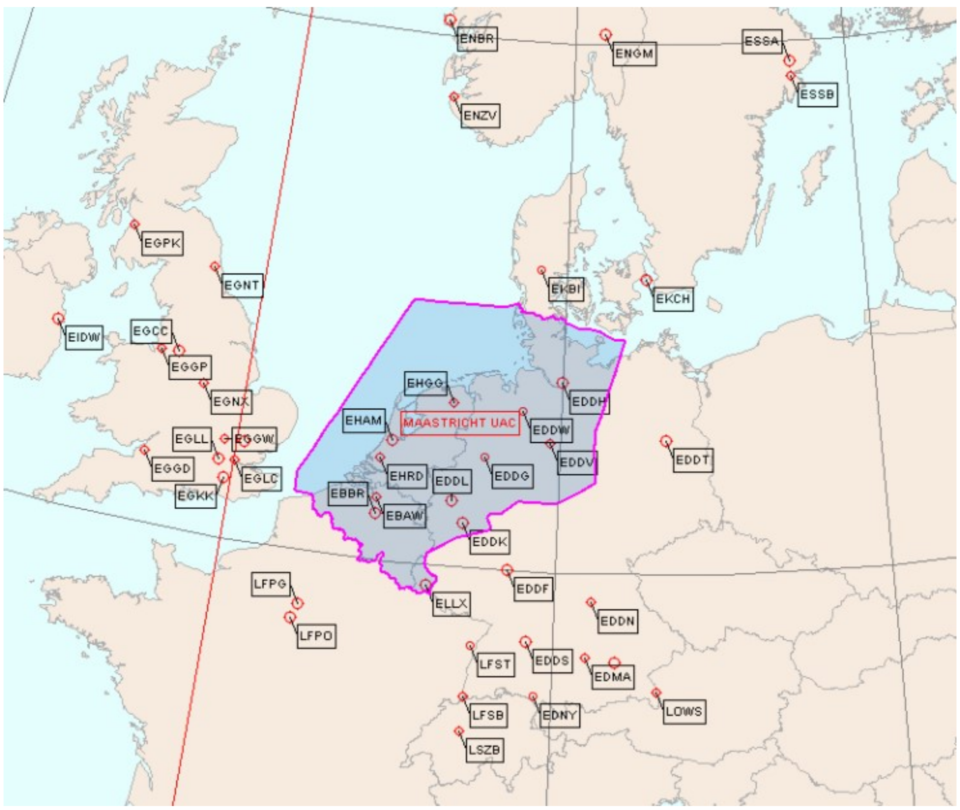


Figure 2.9: Influential airports that impact MUAC's main traffic flows [39]

To effectively manage such a high volume of flights, MUAC is organised on a multinational, civil-military, and cross-border basis. It divides its airspace into three major sector groups with a well-balanced distribution of air traffic throughout the entire airspace. The sectors division can be observed in Figure 2.10. To the South of MUAC airspace is Brussels sector group indicated with the red color. This sector group comprises four sectors, namely Koksy, Nicky, Olno, and Lux sectors. The addition of the Koksy and Nicky sectors was a result of an airspace change prompted by a rise in incidents around the REMBA navaid hotspot.[39] To effectively manage the airspace, all of these sectors are divided into low and high sectors horizontally.

The second big sector group is the DECO sector group. Further, this airspace is divided in Delta, Jever, and Holstein sectors. They are displayed with blue color in Figure 2.10. The particularity of this group is that the Delta sector has three subdivisions, High, Middle, and normal Delta. Last, but not least, with green color the Hannover sector group is shown which is split in Muenster, Celle, Solling, and Ruhr sectors. Out of all of these three sector groups, the Brussels sector group is impacted the most by military activities for which on weekdays, on average, 24% of the volume of Brussels is used for military purposes. [39]

In terms of traffic challenges of MUAC airspace, according to the latest annual report, the traffic of 2021 was only 50% of the traffic from 2019, but there were 12% more flights than the year before. The biggest growth in traffic was seen in Brussels sector group with 14% compared to 2020. In the summer period, MUAC controlled on average 2,800 flights each day. In 2021, MUAC achieved a positive performance of just 4,103 minutes of delay. However, this positive outcome reflects the low volume of traffic still recovering from the COVID-19 period. [31]

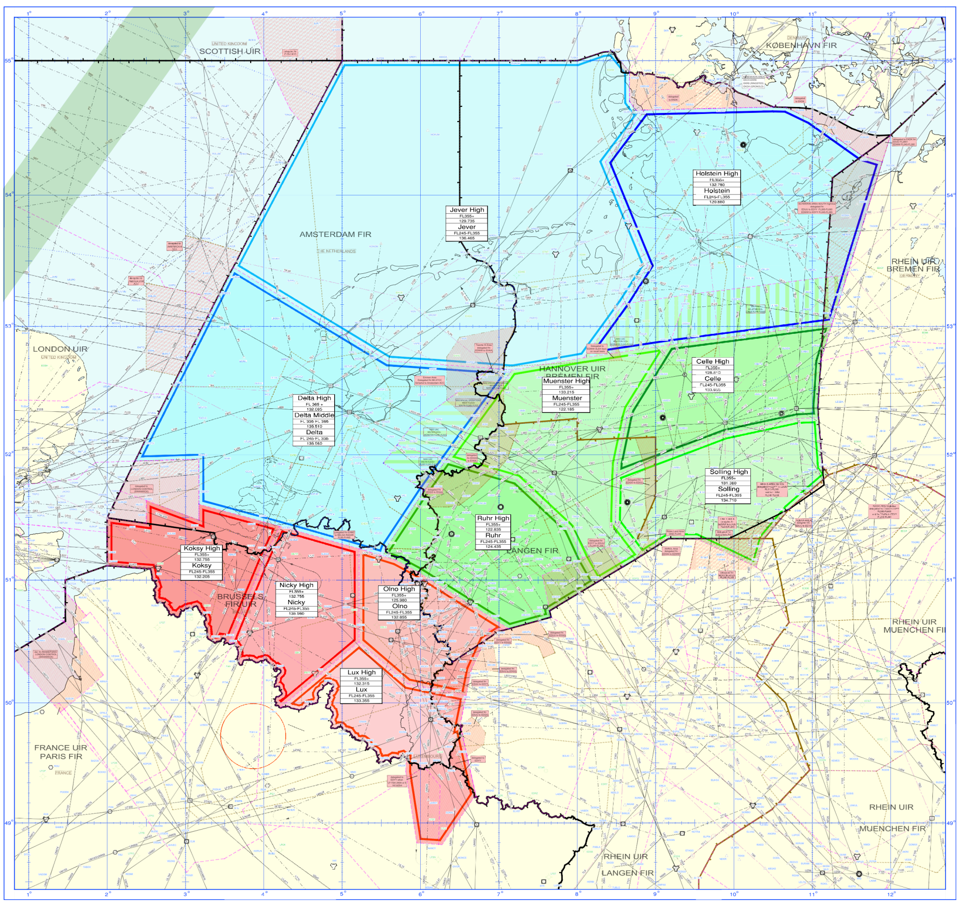


Figure 2.10: The three Maastricht sector groups

2.5. Summary

This chapter focuses on the factors that led to the initiation of this research. It begins with a comprehensive examination of the future growth in air traffic demand, which, how Figure 2.3 displays, is projected to surpass the figures recorded in 2019. This forecast necessitates a stronger analysis, within the ATM system, about how airspace can be optimized. However, the physical constraints, such as the European airspace, pose significant challenges. Moreover, with 56 states comprising the airspace, Europe contains one of the most intricate airspace systems in the world, due to the high number of daily flights.

The structure of Europe airspace and how this is divided by FIRs is presented in Figure 2.5.

By having this in mind the discussion further explores the classification of the European airspace into controlled, uncontrolled, and Special Use Areas. Notably, by analyzing Figure 2.7, the airspace over Europe would become a military zone with commercial flights navigating through it. This intensifies the complexity of the analyzed airspace. Additionally, it was determined that airspace is a complex system where all its components, such as intersections between ATS routes and holding areas, play a critical role in operating it efficiently.

Then, the chapter delves into capacity analysis, highlighting decisive factors considered when analyzing the capacity within sector. These factors include the airspace configuration, ATC workload, navigation capabilities, and safety measurements. The finding of the section is that the capacity cannot be determined by simply counting the number of aircraft, and it needs a more detailed analysis. This analysis includes the exploration of the operational procedures, namely FRA and ATS routes with respect to the level of complexity that these ATM methods impact the capacity within sectors. Finally, the chapter ends with a briefly description of the MUAC airspace. Displayed in Figure 2.9 and Figure 2.10, MUAC airspace is well-known for being busy and complex due to its strategic geographical position and its composition. It is strategically organized into three big sector groups, each group further divided into sectors varying in altitude and spatial orientation.

In conclusion, this chapter aims to provide the necessary background information for the subsequent analysis. The presented information establishes the context of the research and open the study for examining of how different operational methods, such as free routing or ATS route network will affect the capacity with respect to air traffic complexity.

3 Towards Free Route Airspace concept

As it was mentioned in Chapter 2, the determination of capacity within the sector is a complex task influenced by multiple factors. While the air traffic demand and the intricate structure of airspace undoubtedly play crucial roles in determining the air traffic capacity, an equally significant factor lies in the operational methods applied within the sector itself. Currently, two distinct ATM methods are operated. On one hand, there are the traditional procedures that govern air traffic by following the predetermined ATS routes, and on the other hand, there exists the liberty of aircraft to navigate between two predefined points, known as the Free Routing concept.

Therefore, in this chapter, an in-depth analysis is done towards these two different ATM methods, with a meticulous focus on the Free Route Airspace concept. The chapter starts with exploring the traditional procedure, namely ATS routing. In Section 3.1 the purpose of the concept is explained, together with its implementation. Further, the chapter delves into the introduction of the Free Route Airspace. Section 3.2 presents in detail the implementation and legislative aspects, as well as the benefits and drawbacks of this operational procedure. The environmental impact of FRA is mentioned in Section 3.3. Finally, the chapter ends with explaining the MUAC operational environment in Section 3.4 and with a short summary of the chapter in Section 3.5.

3.1. ATS routing

This section explores the fundamental principles and practices that guide aircraft along predefined pathways. ATS routing encompasses the planned network of airways and air routes, offering a structured framework for ATM.

In the early days of aviation, pilots relied on visual landmarks on the ground to navigate their aircraft, as there were no predefined routes to follow. However, with the advent of the first commercial flight on 1^{st} of January 1914, the first scheduled air route was inaugurated. [58] On that flight, one passenger was flown a distance of 29 kilometers between St. Petersburg and Tampa, two cities in Florida state. [2] The flight path is shown in Figure 3.1. As aviation continued to evolve, the demand for air travel grew exponentially, resulting in an upsurge in the number of flights in the world's airspace. As air travel expanded, it became necessary to establish predefined flight paths to regulate the flow of aircraft and to ensure safe separation between them.

This led to an important milestone in the history of airways, namely the publication of the Airway Bulletin No. 1. This document was a collaborative effort between the U.S Department of Commerce and various aviation organisations. It aimed to provide standardized air routes, establishing a more organized system for ATC. [3] The establishment of airways through Airway Bulletin 1 laid the foundation for the development of a global air traffic management system. Over time, this led to a structured framework for guiding aircraft along predefined routes accommodating the increasing volume of air traffic.

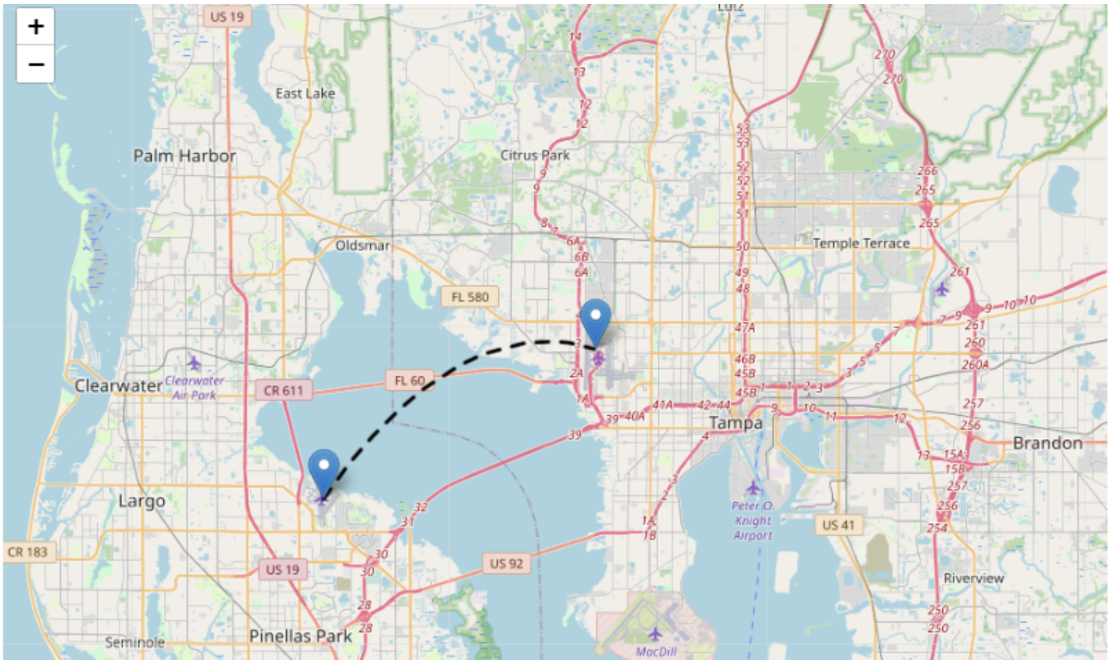


Figure 3.1: The first scheduled air route in the world. Generated with Folium package in Python

As the aviation industry progressed and ATM evolved, the concept of airways transitioned into the concept of ATS routes. This shift in terminology reflects the fact that, nowadays, airways are an integral part of the airspace structure and they are managed by ATS organisations.

By its definition, an ATS route is a path between two waypoints. Sometimes, along the path there may be intermediate points for navigational purposes. A waypoint represents a geographical position determined by the latitude and longitude coordinates, the altitude being ignored. Additionally, it can be designed as a simple point in space or associated with existing navigational aids. For example, in Figure 3.2 the en-route chart for the upper airspace over Amsterdam Airport, EHAM, is illustrated. The triangles near EHAM represent simple waypoints (BASNO and EKROS), while the circles highlight the navigational aids (SPY and PAM).

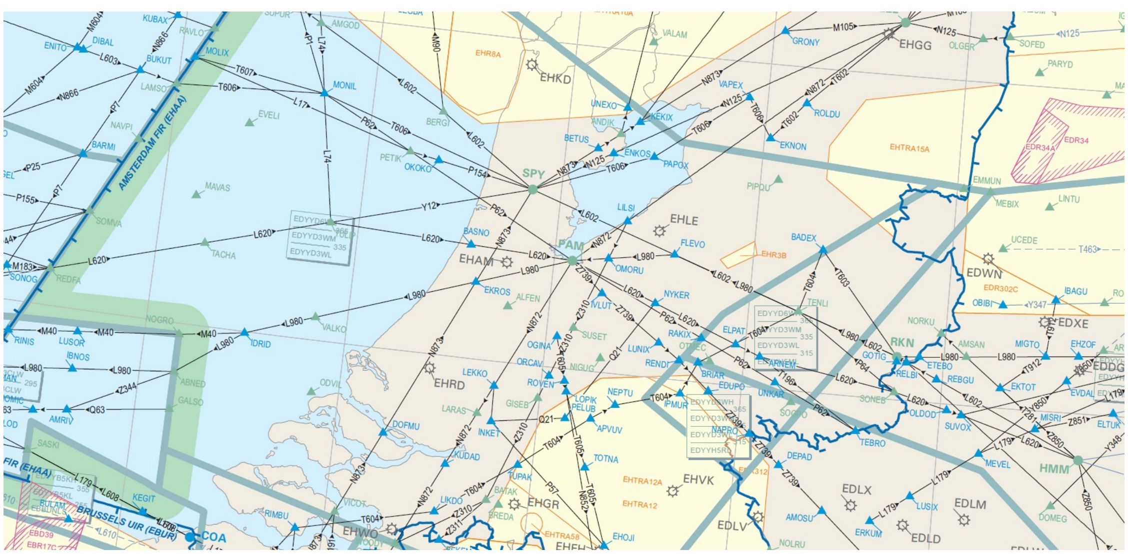


Figure 3.2: Upper airspace navigation chart over Amsterdam airport [27]

The intersection of two or more airways is located at a waypoint. Thus, aircraft can change direction and can change to different airways at such points. In Europe, an ATS route is considered a corridor with a width of 10 NM. [48] It has no physical existence, but it can be seen as a highway in the sky. [60] On a single ATS route, the aircraft is eligible to fly at different flight levels. The difference between flight levels are 1000 ft. However, there are some routes which are bi-directional. Thus, in order to ensure the safety and efficiency along these routes, there is a rule that needs to be applied. According to the course of the aircraft, if the course is situated between $0°$ and $179°$, the aircraft needs to fly on odd flight levels, i.e. FL310. On the other hand, if the course is between $180°$ and $359°$, the flight levels used by the aircraft are even, i.e. FL320. In other words, in the east direction pilots fly on odd flight levels, while in the west direction the required flight levels are even. [5]

Once per month, the basic manual for aeronautical information, Aeronautical Information Publication, AIP, publishes an updated version of the ATS routes. Based on charts, AIP provides information for both en-route and aerodromes. On a chart, the designator of an ATS route may consists of four elements, two of them can be optional. One letter and a number are mandatory, but the prefix and an additional letter are optional. [53]

For instance, in Figure 3.2 there are ATS routes which start with the letter L, M, N or P. An example is L620 which is passing REDFA, TACHA, POLIP, and BASNO to the west of Amsterdam Airport, and PAM, NYKER, ELPAT and so on to east of the airport. These are routes dedicated to area navigation, RNAV, which form part of the regional networks of ATS routes. RNAV represents a method of aircraft navigation that allows for precise and flexible routing within defined areas. Also, Figure 3.2 shows ATS routes starting with Q, T, Y or Z. The difference for these types of routes is that they are not part of the regional networks of ATS routes. For instance, starting from PAM, Z739 passes the waypoints IVLUT, LUNIX, RENDI, continuing further to the south-east of the Netherlands. [53]

3.1.1. Benefits and drawbacks

The implementation of ATS routes comes with several benefits. Among all the benefits, an important one is safety. ATS routes enhance safety in air traffic operations by providing structured and controlled environments. They establish designated routes, and separation standards, ensuring safe distances between aircraft. Air traffic controllers can identify potential hot spots at intersections along these routes, allowing for increased attention and vigilance. Another notable advantage is the efficiency of the air traffic flow. By providing predefined routes and procedures for aircraft to follow, the ATS routes help to optimize airspace utilization. Additionally, in case of adverse weather conditions or low visibility, the network of routes enhances flight guidance and improves the precision of aircraft operations. Aircraft can accurately fly along the routes because they are equipped with navigation aids.

However, among all these benefits mentioned above, there are some limitations associated with the concept of ATS routing. While the ATS routes offers predefined and fixed corridors ensuring the safety between aircraft, they limit the flexibility of the airspace. This may restrict the ability of route optimisation based on real-time factors, such as traffic demand or operational conditions. Following a specific route may create congestions, especially in high-traffic areas or during peak hours. This fixed nature may lead to a high concentration of aircraft along specific ATS routes, resulting in delays and increased workload for air traffic controllers. Also, in emergency situations or urgent circumstances, ATS routes may not provide the necessary flexibility to quickly reroute aircraft or accommodate unforeseen events. This can result in operational disruptions, delays in response, and potential safety concerns.

3.2. Introduction in Free Route Airspace

As aviation technology advances and airspace management is developing, a new concept called Free Route Airspace, FRA, has emerged. While ATS routes have traditionally provided predefined flight paths for aircraft, FRA introduces the flexibility in the air. In other words, the air operators can choose their optimal routes within designated airspace. In essence, FRA aims to address some of ATS routing limitations and provide efficiency in aircraft routing. Thus, this section is dedicated to describe the implementation of the concept, by highlighting its benefits and its limitations.

3.2.1. Implementation of the concept

The ATS routing concept offers multiple benefits on micro and macro levels of airspace management. At the macro level, across the entire airspace network, ATS routes contribute to the overall efficiency of the air traffic management. By organizing the flow of aircraft along predefined routes, airspace can ensure an orderly flow of traffic. In the context of micro level, within a sector for instance, ATS routes enable air traffic controllers to effectively manage coordination and separation between aircraft. However, for a future growth in air traffic demand, the utilization of airspace might be considered a problem if different ATS routes will be overloaded.

A new technology in the ATM system over Europe, based on the concept of a Single European Sky, SES, holds the potential to enhance flight safety and efficiency while mitigating the impacts of increased air traffic demand. The long-term strategy of the SES initiative is to develop air transportation within Europe by increasing the capacity of the airspace while reducing the emissions and flight cost and maintaining a high level of safety. [14] To accomplish these objectives, the SES ATM Research, SESAR, program serves as a collaborative effort from air navigation service providers, airports, airlines, as well as European Commission and EUROCONTROL.

Since 2004, SESAR has been issuing recommendations for modernizing the European air traffic management systems. It represents an aviation development strategy aimed at fostering European economic growth, promoting innovation, and providing passengers with safer travel, and more environmentally friendly flights. By bringing expertise, sharing knowledge, and promoting collaborative projects, SESAR empowers the aviation industry to advance and implement cutting-edge solutions.

Therefore, for more than 25 years, SESAR has worked together with different aviation stakeholders on steadily improving the European ATS network. A significant step towards a solution for the extension of the airspace and more flexibility in the air was made by the establishment of Free Route Airspace. The coordinated implementation of this concept was initiated in 2008 and since then the European environment has changed, being the first region in the world who has implemented such operations.

By its definition, FRA gives the airlines the opportunity to plan their route within an airspace without using any airways. It provides the freedom of choosing the preferred routes without being tied to the established ATS route network. FRA is characterized by horizontal boundaries which are defined by entry-exit points. The distance between these two point cannot be bigger than 200 NM. If the intended route spans a distance greater than 200 NM, an intermediate point must be included in the flight plan. Furthermore, in situations where there is a flight level change or change in flight rules, pilots are also required to include an intermediate point in their flight planning.

There are five FRA significant points that are typically defined on FRA charts. The first two points are the FRA Horizontal Entry and Exit Points, noted by E, respectively X. FRA (E) marks the location where aircraft are allowed to enter and commence FRA operations, while FRA (X) represents the horizontal boundary where FRA operations conclude. In addition to these points, there are the connecting points, the FRA Arrival Connecting Point, A and the FRA Departure Connecting Point, D. These points facilitate the connectivity between FRA and specific aerodromes. Lastly, the FRA Intermediate Point, I, is another significant point in the FRA system. More over, a single point can serve multiple functions within the FRA. A point can be designed as both intermediate and connecting point, for instance.

An example of free routing can be observed in Figure 3.3. To illustrate the concept better, consider an aircraft flying over Romania, originating from the southeast and heading to a destination in western Europe. In a scenario involving the ATS route network, once the aircraft enters the Bucharest FIR through the entry point of ARGES, it would typically be directed to follow a specific sequence of airways until the exit point of MOPUG. This involves following the westbound ATS route T746, then changing towards the bidirectional route M747, and finally flying to MOPUG on another westbound ATS route, P975. The route is defined by black line color.

On the other hand, within FRA, the aircraft has the freedom of a more direct route. Instead of adhering to the ATS route network, the aircraft can plan a route that connects the entry point ARGES directly with the exit point of the Romanian airspace, MOPUG. The free route is highlighted by the green color.

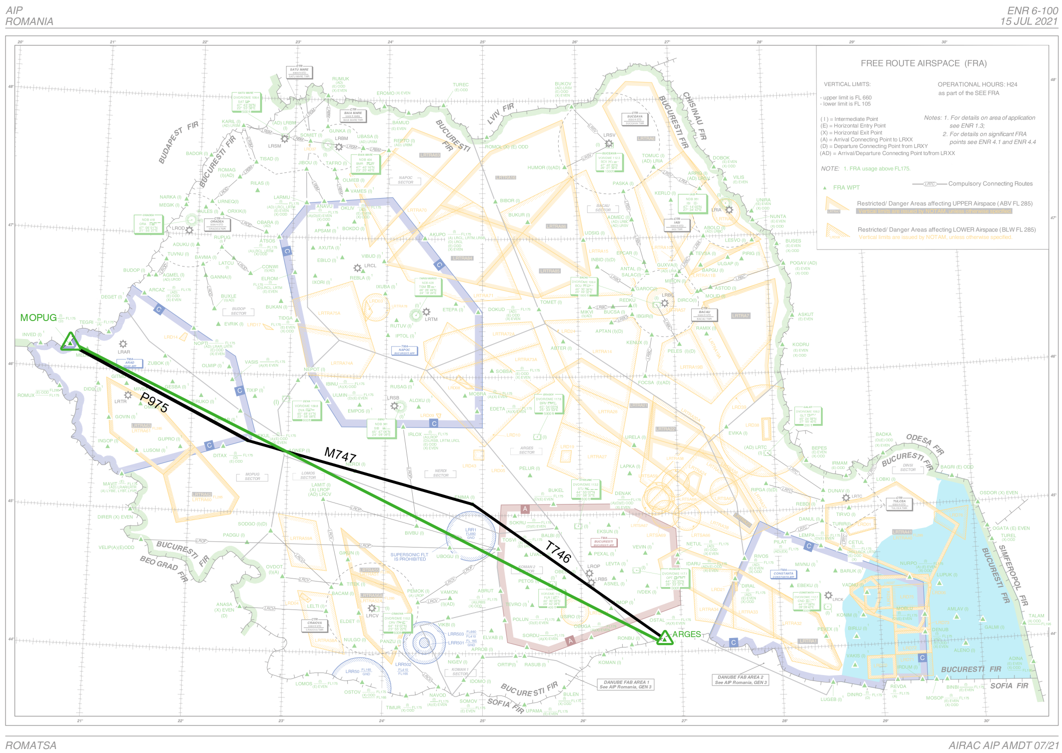


Figure 3.3: Illustration of ATS routing and FRA within Romanian airspace. Created based on En-route Charts of Bucharest FIR [73]

The FRA implementation does not impose a minimum flight level requirement. As a result, the implementation of free routing may vary across different states. Some airspace areas adopt the FRA in both lower and upper airspace. An example in this case is Romanian airspace, where the minimum flight level of the free area is FL105. [73] In contrast, other regions implement FRA just in the upper airspace while maintaining a structured ATS route environment in the lower airspace. Consequently, a change in level may be required to leave the free airspace via an intermediate point, which is prior to the transition and which coincides with an ATS route below the FRA. An example of this type of airspace structure is Zagreb FIR. [12]

In the context of connectivity between Free Route Airspace and aerodromes located below, the specific airspace structure plays a pivotal role from a flight planning perspective. Depending on the configuration, the aircraft may need to join the ATS route network to facilitate their arrival or departure procedures. The Romanian FRA, which includes the lower airspace, can be considered an example. In this case, the flight planning of the aircraft shows that the aircraft is following the STAR that connects the FRA directly to TMA. In Figure 3.4 the aircraft with origin from west and with its destination Bucharest Airport needs to enter the Bucharest TMA via the connecting point TOSVI. Similarly, this principle applies to departing aircraft from Bucharest.

However, in the case of arriving and departing traffic from aerodromes located in an airspace with FRA and ATS route network, the aircraft needs to establish procedures and join the specific ATS route as required. To illustrate this, the example of Zagreb Airport in Croatia, which is shown in Figure 3.5, is considered. Aircraft approaching this airport from the east, within the FRA, must plan their flight to exit the FRA vertically via a designated point, called KOPRY. Then the aircraft needs connect to the STAR via the ATS route network. This enables a seamless transition from the FRA to the airport's arrival procedures, ensuring proper sequencing and integration with other arriving traffic.

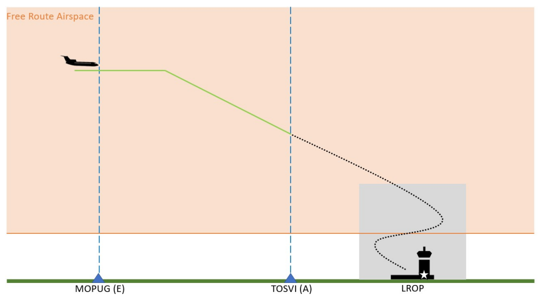


Figure 3.4: Vertical Connectivity - Romanian airspace

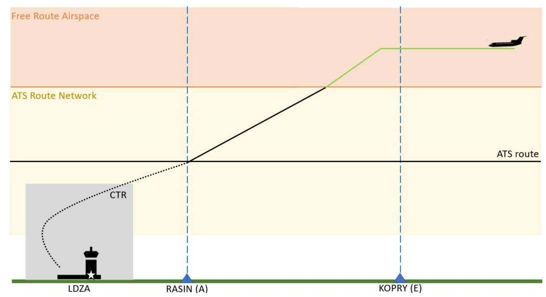


Figure 3.5: Vertical Connectivity - Croatian airspace

As it can observed from the examples mentioned above, in contrast to the Free Route Airspace implemented in the en-route environment, airports have specific operational considerations that necessitate the adoption of distinct procedures. Therefore, FRA is not extended to the airspace of the airports. This approach aims to manage air traffic flow and minimize congestion, delays, and potential safety issues associated with vertical movements near by aerodromes.

The collaboration between more states, which implement Free Route Airspace, introduces a new level of flexibility and efficiency for airspace users resulting in more direct routing. By aligning their airspace policies and harmonizing FRA implementation, the aircraft can navigate direct from the entry point to the exit point bypassing the need to follow specific airways associated with individual states. The cross-border expansion can be achieved in two different ways. It can be a merged airspace, a single FRA area or multiple FRA areas where cross-border FRA operations between them are allowed. For a cross-border FRA operations, there are no FRA (E) or FRA (X) points on common borders. These points are swapped to FRA (I) points.

3.2.2. Current situation over Europe

Europe has been the first region which implemented the Free Route Airspace. According to Commission Implementing Regulation (EU) 2021/116 [10], the implementation has been carried out in two distinct phases. The initial phase involves the implementation of FRA with certain time and structural constraints, while the final phase represents the establishment of a fully operational FRA with cross-border operations and connectivity with the Terminal Areas of aerodromes. In addition, FRA is implemented across three dimensions. Horizontally, where the airspace is delimited by entry-exit points, and vertically where the free routing technology can be implemented across multiple flight levels. The third dimension is time, as FRA implementation can vary depending on operational hours. Several countries in Europe have embraced FRA and adopted different operational models. Romania, Sweden, and Finland, for example, have the full 24-hour FRA concept, while Germany and Austria have implemented FRA specifically for the core night period.

From a geographical perspective, Free Route Airspace has been successfully implemented in most of the countries from the EUR region. Portugal holds the distinction of being the first country which introduced the full FRA operations on 7^{th} of May 2009. [32] Over time, the implementation of FRA has expanded across Europe, with the goal of achieving the final FRA implementation in most of the continent's airspace by the end of 2025.

By the end of 2023, the implementation of Free Route Airspace across Europe is expected to be identical with the representation in Figure 3.6. The majority of countries will have implemented FRA operations on a 24-hour basis. Additionally, certain states will only have the airspace open for free routing during the night. This includes the north-west part of Morocco, Turkiye, and Cyprus. Similarly, in several sectors of Germany, the implementation time-period of FRA will vary based on the flight level, with some sectors operating on a night-only basis, while others have 24-hour FRA operations.

Despite the significant progress in free routing approach, there are still part of the airspace where its implementation is pending. This includes specific areas in countries such as Morocco, France, and the United Kingdom. The red markings in Figure 3.6 represent the cross-border for FRA. In the context of cross-border operations, FRA enables uninterrupted flight planning and operations between neighboring countries. This concept promotes the airspace harmonization and interoperability between the countries of the EUR region.

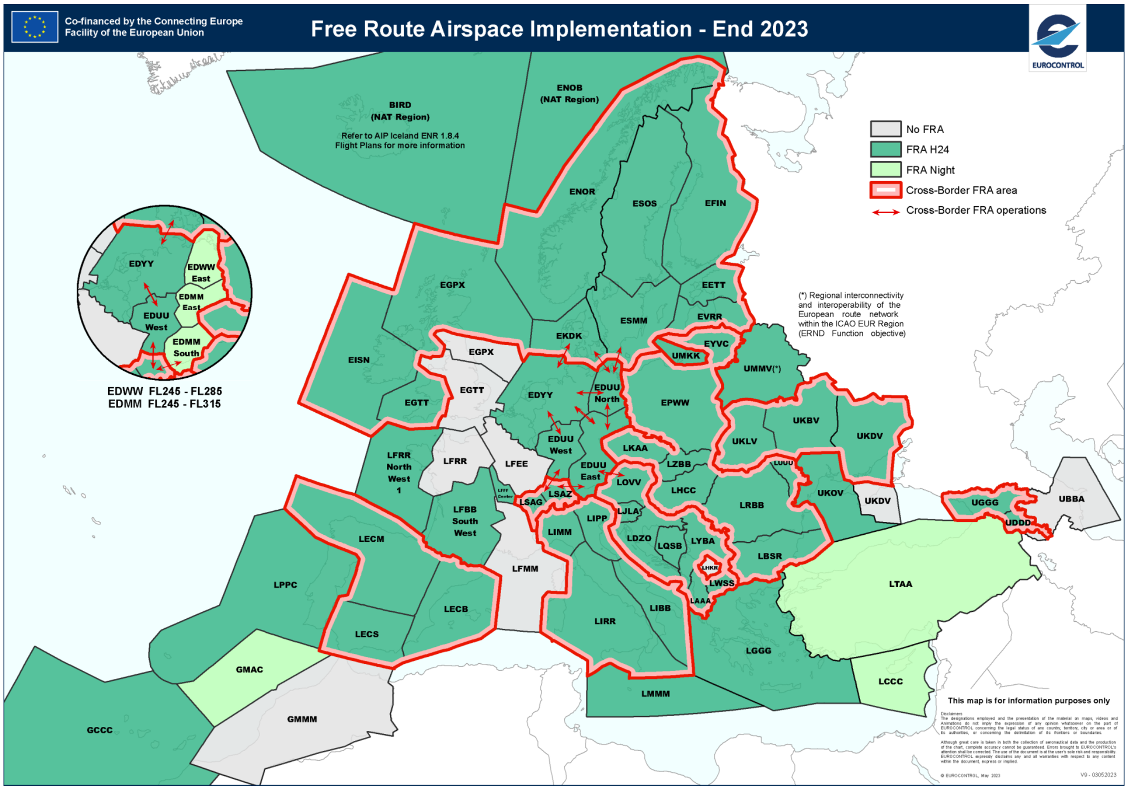


Figure 3.6: Free Route Airspace Implementation - End 2023 [32]

3.2.3. Benefits and drawbacks

According to [32], the full implementation of FRA technology on a macro level across Europe will bring significant improvements for the ATM in terms of distance, time, emission, and cost in the upcoming years. One of the key targets set by EUROCONTROL is that by the end of 2030 there will be a saving of 1 billion NM in terms of flight distance. This reduction in distance traveled will contribute to environmental sustainability by reducing the CO_2 emission by 20 million tonnes. Additionally, EUROCONTROL aims to achieve 5 billion euros in fuel cost savings, demonstrating the economic benefits of FRA implementation. Throughout time, FRA implementation started to offer benefits that helped achieving the proposed targets of EUROCONTROL. Therefore, important progress has been made in improving the overall ATM system, particularly in terms of the route extension metric. As a result of the implementation of FRA technology across three-quarters of European airspace, the difference between the flight flown and the corresponding portion of the great circle distance, has seen notable decrease of 1.5% over the years.[32]

The impact of FRA implementation on airspace management represents a very popular topic in literature. In the Hungarian airspace, the full implementation of FRA was done in 2015. [13] makes an assessment based on the changes in traffic flow and human performance within this new technology. The findings of the study reveal that FRA can cause a shift in the traffic flow from a previously organized state, like in an ATS route network to a disarranged one, as depicted in Figure 3.7. This disarranged traffic flow leads to a more even distribution of the same volume of traffic throughout the airspace, which may result in enhancing the overall capacity of the airspace. However, this disarrangement can create more complexity of the airspace.

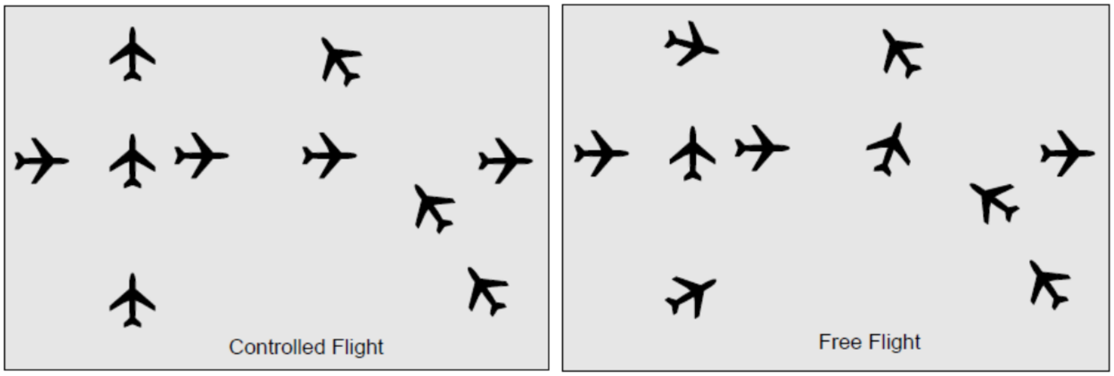


Figure 3.7: Flow of traffic in controlled flight vs free flight [13]

Another study, conducted by [44], employs an empirically grounded agent-based simulator to analyze the implementation of FRA with respect to safety and complexity aspects. The interesting finding that the study reveals is that the air traffic controllers are responsible for fewer operations within the FRA framework compared to the traditional ATS route environment. However, these operations are spread out across a larger portion of the airspace. Consequently, the introduction of FRA may result in a trade-off between controllability of aircraft and the overall workload of an air traffic controller.

Another benefit that free routing brings, is the collaboration between states by cross-border operations. FRA implementation expands the airspace through cross-border operations, enabling aircraft to navigate directly from entry to exit points without additional requirements from the ATC units. This leads to interoperability between states and it facilitates more efficient traffic flows. However, ensuring safety within the airspace remains a critical factor that needs to be taken into consideration. As highlighted in [44], a larger airspace, due to the implementation of FRA, can potentially increase the workload for air traffic controllers due to the expanded area of control. Furthermore, two different studies conducted on Northern Europe Free Route Airspace, NEFRA, have examined the safety implications of FRA deployment. Based on a fast-time simulation model, [40] indicates that the safety levels did not change during the implementation of FRA. Additionally, [66] conducts a post-operations assessment on NEFRA, and their time series analysis reveal a positive impact of FRA on safety performance, even in the face of sustained traffic growth. These findings demonstrate that FRA implementation can enhance safety within certain airspace areas.

Moreover, more studies conclude that cross-border operations within FRA contribute to the increase of efficiency in air traffic management. Performing an optimisation of the routes passing through two Free Route Airspace areas in Portuguese airspace, [67] indicates that by combining the two FRAs, a significant saving of around 500,000 NM per year could be achieved, which means around 7 NM saved per aircraft.

Furthermore, the implementation of FRA may reduce some aspects of the traffic complexity. [70] demonstrates that detecting conflicts within FRA is notably more challenging compared to airspace defined by traditional ATS routes. Based on real-time simulation results, [76] concludes that FRA present challenges in identifying conflict situations and finding appropriate operations for resolution because the air traffic controllers have fewer options available for resolving the traffic conflicts in FRA. One possible explanation for this is that, under the conventional ATS route environment, air traffic controllers have the ability to direct aircraft onto predefined routes, whereas aircraft operating within FRA already follow direct paths, requiring air traffic controllers to adopt different strategies. In an ATS route network, the air traffic controllers may adopt the strategy of giving the aircraft the direct command, which means that the aircraft will not follow the conventional route anymore and it will fly direct from one waypoint to the other. This procedure can be associated with the concept of free routing.

In conclusion, FRA brings numerous benefits to the ATM system, including shorter routes, cost savings in fuel consumption, and environmental sustainability. It also shows a positive trend in increasing airspace capacity compared to traditional ATS routes, by its flexibility of free routing planning, which allows more efficient use of airspace. However, it is important to acknowledge that the implementation of FRA can introduce a level of complexity to the airspace and to the air traffic controllers workload. While FRA enhances physical capacity, it also affects other factors that can potentially reduce overall capacity. Due to the larger operational area, the workload for the air traffic controllers may increase. Additionally, the potential for conflict detection and resolution may be heightened since the intersection of two or more flights paths are in ”invisible points”.

Thus, to comprehensively analyze the impact of FRA on airspace capacity and traffic complexity, it is necessary to establish a description of complexity concept, which will be explored in detail in the subsequent chapter, Chapter 4. These findings underline the importance of future research in developing effective solutions to address these challenges.

3.3. Environmental impact of aviation

Aviation, like other transport industries, has an environmental impact that extends beyond its immediate benefits. The environmental impact of aviation refers to the effects that aircraft operations and related activities have on the natural surroundings, including the atmosphere, ecosystems, and human health. As a rapidly growing industry, with a future traffic growth in demand and more advanced technology that will enhance the capacity in the air, aviation plays a significant role in global emissions and pollution. Therefore, it is essential to address these environmental implications, which will be done in this section.

Presently, aviation constitutes a relatively small sector within the overall transportation industry in terms of its contribution to climate change. However, as the demand for air travel continues to increase, the climate impact of aviation is expected to increase simultaneously. Thus, it is essential to address several climate change aspects while considering the enhancing of the capacity within sectors.

The climate impact of aviation results from two types of emissions, namely CO_2 and $non-CO_2$ emissions. Due to its long atmospheric lifetime and significant contribution to radiative forcing, CO_2 is recognized as a greenhouse gas agent in aviation. But, aircraft emissions also consist of other substances. These $non-CO_2$ emissions, such as nitrogen oxides, water vapors, aerosols, and so on, have shorter lifetime but have a bigger climate impact, especially when emitted at cruising altitudes.

[78] indicates that aviation’s contribution to anthropogenic warming is a combination of CO_2 and $non-CO_2$ emissions. Approximately, one-third of the global warming effect is attributed to CO_2 emissions, while the remaining two-thirds result from $non-CO_2$ emissions. As a significant source of greenhouse gas emissions, it has been determined in [78] that the worldwide CO_2 emission per year due to aviation is 1 gigaton, Gt, per year, accounting for roughly 2.5% of the total CO_2 emissions.

Regarding the aircraft operations’ environmental fingerprint, several factors contribute to climate change, including nitrogen oxides, NO_x, aviation water vapor, and contrails. NO_x, i.e. NO and NO_2, are significant $non-CO_2$ emissions that contribute to the overall warming effect. They result from the aircraft engine and combustor architecture. The climate impact of water vapor emissions, without contrail formation, is relatively small, especially at subsonic speeds. However, the impact increases with altitude due to longer lifetimes and lower background concentrations at higher altitudes. Water vapor emissions play a role in the greenhouse effect and can contribute to the warming of the atmosphere.

Contrails, on the other hand, are the visible trails of condensed water vapor and ice crystals that form when hot engine exhaust mixes with cold air at high altitudes. Contrails can have both cooling and warming effects on the Earth’s climate. Initially, they tend to have a cooling effect by reflecting sunlight back into space. However, they can also trap heat radiated from the Earth’s surface, leading to a warming effect. In addition to their radiative properties, contrails can persist and spread, forming thin, high-altitude cirrus clouds. These cirrus clouds act as a greenhouse layer, trapping outgoing infrared radiation and contributing to the overall warming of the atmosphere.

To maintain the a sustainable environment, it is essential to search for climate impact mitigation options. Despite the annual increase in air traffic presented in Section 2.1, a reduction of the climate impact have to be addressed. Section 3.2 describes the operational method of free routing where the positive effect of reducing the flight distance from origin to destination on the time of flight is mentioned. Thus, in Section 3.3.1 is presented how the concept of Free Route Airspace can increase the sustainability in the aviation industry.

3.3.1. Impact of Free Route Airspace on environment

As it was mentioned in Section 3.2, the implementation of FRA plays a positive role in sustainability of air transportation. Being a very important topic, many studies conducted research on the FRA implementation with respect to the environmental impact. For example, [7] focuses on the advantages of FRA in Europe, specifically in terms of cost reduction and fuel savings. Their findings demonstrate that the potential fuel savings achieved through FRA implementation contribute to a reduction in overall greenhouse gas emissions.

Another study regarding the environmental benefits from FRA was performed in detail by EUROCONTROL. This study involved the participation of eight countries, namely Belgium, Denmark, Finland, Germany, Luxembourg, Netherlands, Norway, and Sweden. All of these countries create the simulated airspace, called Free Route Airspace Project, FRAP, area. The study aims to assess the environmental impact of the FRA implementation, particularly in the upper airspace segments. [51] indicates that the FRA concept leads to a reduction in fuel burn of up to 2.1%. This reduction in fuel consumption directly translates into lower NO_x and CO_2 emissions. The overall trend indicates a positive impact on decreasing the emissions.

Based on an analysis of the Free Route Airspace over the North Pacific, [45] shows a positive trend of increased efficiency of the free routing environment with an average of fuel consumption savings of almost 1300 kg for both directions, eastbound and westbound. Also, the study indicates that FRA concept over the North Pacific can improve capacity and efficiency while maintaining or increasing safety. In addition, a simulation of south-east Europe Free Route Airspace was conducted in order to analyze the environmental impact. The result reveals that the implementation of FRA has the potential of saving up to 10,000 NM which represents a reduction of 220 tons in CO_2 emissions on a busy day. [8]

3.4. Overview of MUAC operational environment

To ensure a comprehensive understanding of the MUAC operational environment, it is necessary to examine the flow and operational procedures implemented within its airspace. Thus, this section provides the overview of how MUAC is operated, where the main flows are and whether it follows the traditional ATS route network or incorporates the innovative Free Route Airspace concept.

As mentioned in Section 2.4, MUAC airspace represents one of the busiest and most complex airspace areas in the world. Being positioned in a strategic geographical region, between main airports of Europe and connecting the East of Europe with the Atlantic Ocean, MUAC is operating all the flights which are above FL245. In its network there are four main traffic flows. Thus, MUAC handles the traffic between the northern European airports and Paris or the southern European airports or the traffic between London and German or central European airports. The northbound, southbound, eastbound, and westbound of MUAC traffic can be seen in Figure 3.8.

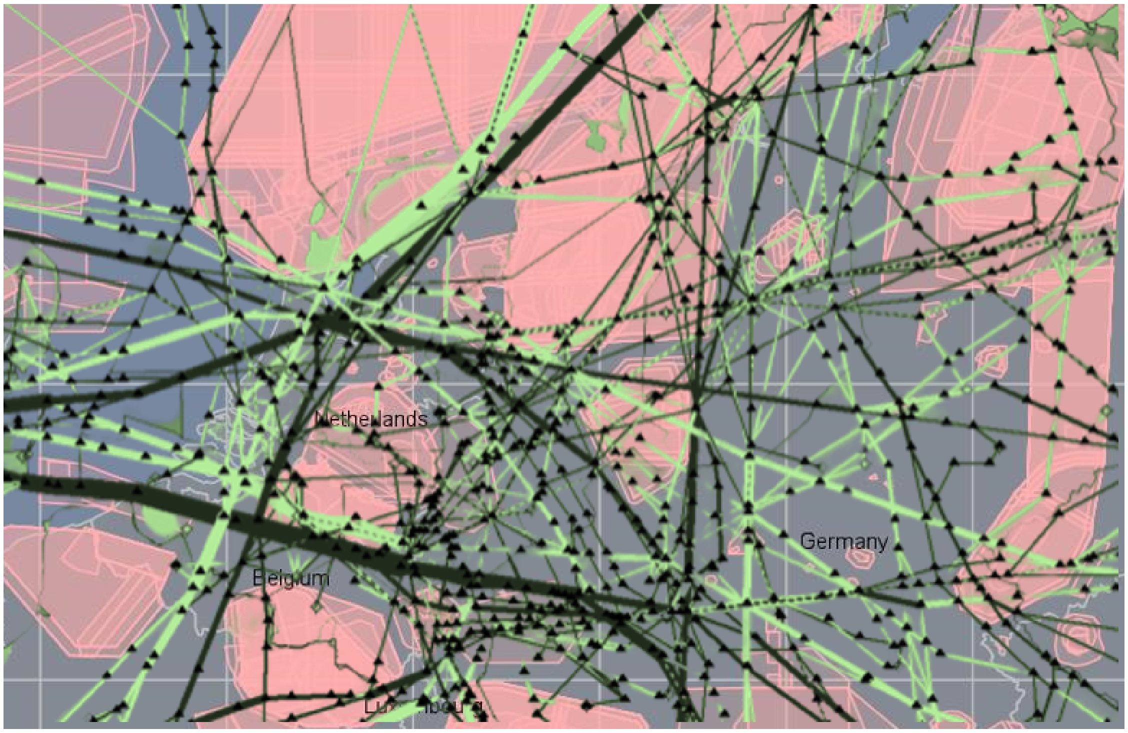


Figure 3.8: Main traffic flows related to MUAC. Generated by CHMI and adapted after [39]

Starting in 2019, airspace user within the MUAC airspace were granted the significant advantage of free routing. On 5^{th} of December 2019, the implementation of FRA became operational 24 hours a day. This implementation of FRA is covering the whole upper airspace, covering flight levels from FL245 up to FL660. The introduction of FRA within the MUAC airspace marks a notable shift in air traffic management practices. It allows aircraft operators the freedom to plan and navigate their routes directly from entry to exit points, without the need to adhere strictly to predefined air traffic service (ATS) routes. However, below FL245 an ATS route network still exists, but these airspace areas are typically managed by the respective lower area control centers. For example, in Brussels FIR the national organization Belgocontrol is responsible for controlling the traffic below FL245, while in Germany, DFS Deutsche Flugsicherung is in charge of all the air traffic below MUAC airspace. Nevertheless, these ANSPs coordinate and collaborate with MUAC for the seamless management of air traffic across different flight levels and airspace sectors. The en-route of Free Route Airspace at Maastricht UAC can be seen in Figure 3.9.

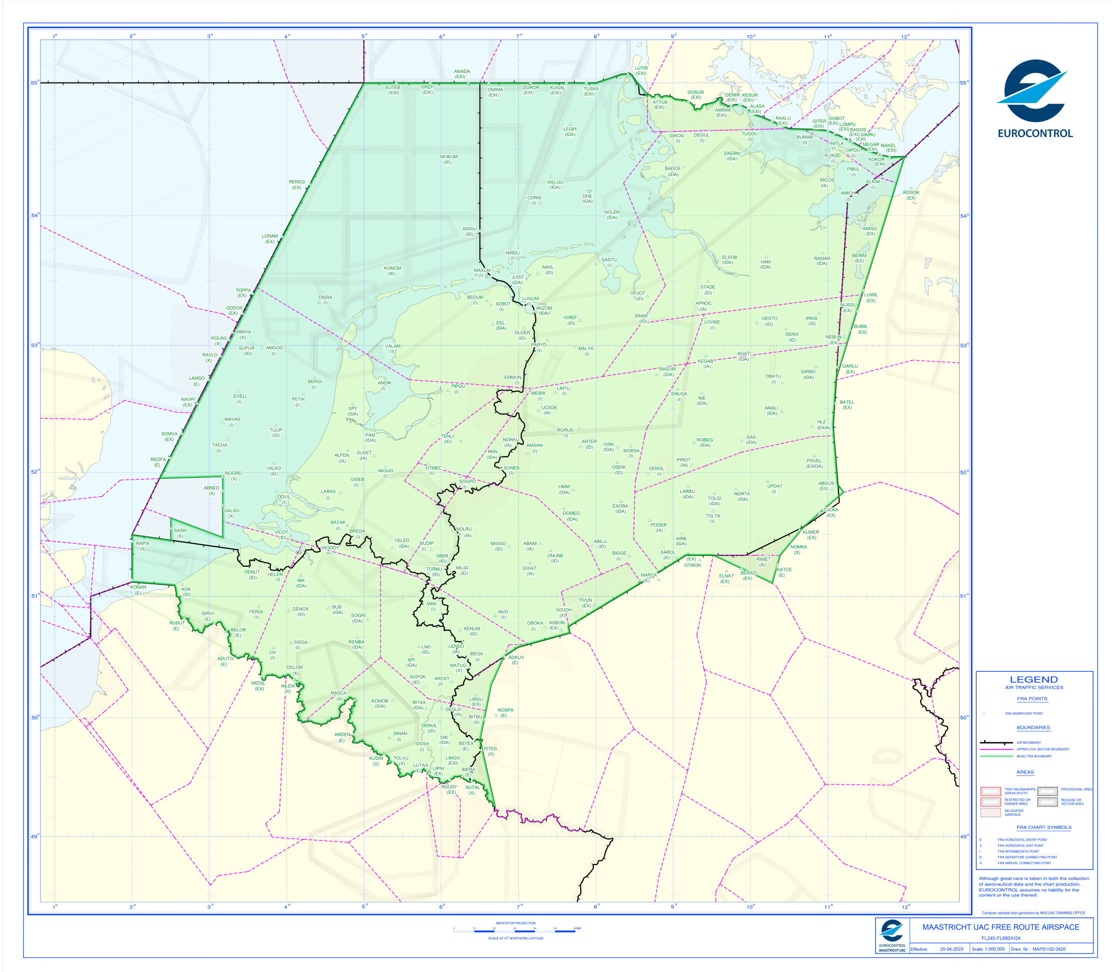


Figure 3.9: Maastricht UAC Free Route Airspace [33]

Within MUAC Free Route Airspace, aircraft need to follow some ATC procedures. To ensure smooth operations and effective coordination, aircraft must comply with the designated times of availability for FRA entry points, departure or arrivals points, exit points, and intermediate points. These availability times are established by air traffic control and serve to maintain orderly traffic flows and enhance airspace efficiency.

MUAC, as part of the Functional Airspace Block Europe Central, FABEC, plays a significant role in the Free Route Airspace programme. The Free Route Airspace Maastricht and Karlsruhe (FRAMaK) project, conducted between June 2012 and May 2014, was a collaborative effort funded by the SESAR Joint Undertaking. Its purpose was to showcase the capabilities of cross-border free route airspace operations in complex and high-density airspace. Thus, starting from April 2019, cross-border FRA was implemented in the upper airspace of Belgium, Luxembourg, the Netherlands, Germany, Denmark, and Sweden. All this airspace is handled by the collaboration between MUAC, DFS Deutsche Flugsicherung, LFV, and Naviair.

3.5. Summary

The chapter focuses on the implementation of Free Route Airspace in Europe, exploring the benefits and drawbacks that this operational procedure may involve. In order to understand this concept, an analysis of the traditional operational environment is presented. Thus, the ATS routing method is discussed in Section 3.1.

In this approach, flight paths are considered ATS routes, which represent corridors with a width of 10 NM between two waypoints. Waypoints are defined as navigational aids or just simple points in the air. These waypoints always have intersections of two or more ATS routes. In an ATS route network, aircraft may follow certain rules. For example, on the vertical profile, aircraft can fly at different flight levels, with a difference of 1000 ft between each level. In addition, ATS routes are categorized into three types, namely eastbound routes, westbound routes, and bi-directional routes. While bi-directional routes allow the traffic to fly in both directions, the eastbound and westbound are delimited by the altitude. For the eastbound traffic, aircraft are eligible to fly at odd flight levels, such as FL310. In contrast, in westbound ATS routes, aircraft fly at even flight levels, i.e. FL320. These ATS routes are updated monthly and published in AIP.

Further in the section, several benefits and drawbacks that ATS routing brings to the ATM systems are presented. For example, the organized airspace enhances safety, as air traffic controllers are familiar with areas that require increased attention, such as intersections between multiple ATS routes. By providing standardized routes, the ATM system can optimize the airspace utilization. However, there are some limitations associated with the ATS routing approach. The fixed nature of the network may lead to a high concentration of aircraft along specific ATS routes, potentially resulting in congestion. Moreover, the inflexibility of airspace users to take shorter paths by having a more direct route from origin to destination can lead to sub-optimal routing and increased flight distances. As a result, the fuel burn increases, as well as the environmental impact.

To address these limitations and enhance airspace efficiency, the concept of Free Route Airspace has been described in Section 3.2. This section of the chapter will delve into the implementation of FRA, offering benefits and drawbacks of the technology.

The free routing technology gives the opportunity to the airspace user to freely plan their route, resulting in time, fuel, and cost savings. This concept operates both horizontally, from entry to exit points, and vertically across different flight levels. While there is no specific minimum flight level for implementing Free Route Airspace, around the airports, aircraft need to adhere to specific procedures and standards defined by the specific aerodromes. Connectivity between FRA and aerodromes located below this airspace requires specific procedures to be taken into consideration. Depending on the airspace configuration of the country, aircraft may need to transition from FRA to the ATS route network before approaching the airport.

Currently, over three quarters of Europe have already implemented this concept. Countries that have implemented FRA can choose between full 24-hour FRA operations or partial FRA operations, where FRA is implemented during specific night hours. Portugal was the first country to fully implement 24-hour FRA operations in 2009. In addition, FRA implementation allows for cross-border operations, enabling collaboration between multiple states within a single or multiple defined FRA areas. In this case, the entry and exit points of the Free Route Airspace from one country must coincide with those of the other country.

Similar to ATS routing, FRA has its own benefits and drawbacks. In terms of distance, time, emissions, and cost, FRA brings significant improvements to air traffic management. The distance flown by aircraft within FRA is considerably reduced compared to following traditional ATS routes, resulting in time and fuel savings for airlines and reduced emissions from aviation. FRA has been shown to enhance overall capacity while maintaining a high level of safety. However, it is unclear whether FRA can maintain a low level of workload for controllers or address other measures of traffic complexity. On the other hand, by flying free, aircraft will transform the organized airspace in one which is more disarranged, resulting in producing invisible intersections between two or more flight paths. These intersections may not be as easily detectable as they are when aircraft follow ATS routes. Moreover, in the ATS routing environment, the air traffic controllers may adopt the strategy of giving the aircraft a direct command in order to minimize a potential conflict. This means that aircraft is altering its path for a free route between two points. However, aircraft operating within FRA already follow direct paths, requiring air traffic controllers to adopt different strategies in managing the traffic.

The impact of aviation on the environment is a significant and widely discussed topic. In Section 3.3, the environmental impact of en-route operations is addressed, with a focus on the positive aspects of Free Route Airspace in terms of sustainability. This highlights the potential of FRA to mitigate the environmental impact of aviation.

Further, Section 3.4 provides an overview of the operational environment at MUAC. MUAC represents a very busy airspace which connects the main flows from between the northern European airports and Paris, the southern European airports or the traffic between London and German, central European airports. The implementation of FRA in this airspace had been performed later than for other countries in Europe. In 2019, the airspace could be operated via free routing the entire day. More than that, being a part of FABEC, MUAC allows the cross-border operations among this Functional Airspace Block, FAB. The collaborative management of air traffic within MUAC involves the participation of multiple entities, including Deutsche Flugsicherung, LFV, and Naviair.

In conclusion, considering the projected growth in air traffic and the potential benefits of Free Route Airspace, it becomes essential to examine the feasibility of enhancing sector capacity while simultaneously addressing the complexities associated with FRA implementation. This includes ensuring safety, managing air traffic controller workload, and maintaining overall system efficiency. Thus, the concept of complexity and how it can be measured within FRA technology will be the topic to discuss in the following chapter, Chapter 4.

4
Air traffic complexity

Air traffic complexity plays a critical role in the management of airspace and in air traffic control operations. Implementing Free Route Airspace introduces a new dimension to the airspace environment, requiring a detailed understanding of the operational system and its interaction with the physical environment. As the demand for air travel continues to grow, it becomes more and more important to manage complexity in order to ensure the highest levels of safety and operational efficiency. By analyzing the complexity metrics, which can be associated with the FRA implementation, solutions for managing the airspace efficient in the face of increasing traffic demands can be provided. Thus, this chapter delves into the concept of air traffic complexity, highlighting its characteristics and several methods for measuring the complexity.

The chapter starts with an introduction about the complexity concept, examining how it is defined in the existing literature and its interpretation from an engineering manner. This introductory part is described in Section 4.1. Further, Section 4.2 delves into the concept of sector complexity from aviation perspective. Then, Section 4.3 focuses on exploring the complexity factors in detail. It presents various elements that contribute to complexity of air traffic. Moving forward, in Section 4.4 the examination of the metrics used to assess and quantify the level of complexity within a sector is described. Finally, the chapter concludes with an overview of MUAC's traffic complexity in Section 4.5. All the key points discussed throughout the chapter are presented in Section 4.6.

4.1. Complexity concept

Complexity has been defined in many different ways, and synonyms such as complication, difficulty, intricacy, and ramification are often associated with it. In the Oxford Dictionary and the Collins Online Dictionary, complexity is described as being a state of many parts. While the Oxford Dictionary introduces the notion of difficulty with respect to complexity, such as ”a state of many parts which is difficult to understand” [22], in the Collins one, ”all the parts are related to each other in a complicated way” [21]. In addition, the Cambridge Dictionary defines complexity as a feature that makes something hard to find answer to. [20] All of these definitions have a common point, as a result of a system based on more elements which are intricately interconnected. The relationships and dependencies of the elements within the system contribute to the challenges in comprehending the system as a whole.

However, even if complexity has been associate with number of elements or complications, there is no direct connection between them. Certainly, a system can be complicated without being complex. Even though a larger numeric size of elements may correspond to a higher level of complexity, this number alone cannot be directly related to the system's complexity.

In general, the complication originates from causes that can be distinguished individually. In contrast, complexity arises when all the elements interact with each other by creating a network which needs to be addressed as an entire system. For clarifying the distinction between a complicated and a complex system, lets consider a system consisting of four elements: body, actuators, controls, and power supply. The diagram of the system can be observed in Figure 4.1. Each element represents a system itself, leading to a large amount of factors for the whole system.

Hence, as a complicated system the car system with its four main components can be considered. The body represents the framework of the car, the actuators correspond to the transmission system, the power supply refers to the engine, and the controls are represented by the chassis. The car system is represented in Figure 4.1 with the green color. On the other hand, the health system represents an example of a complex system. It encompasses the social, physical, spiritual, and intellectual aspects. This system is marked by the pink color in Figure 4.1.

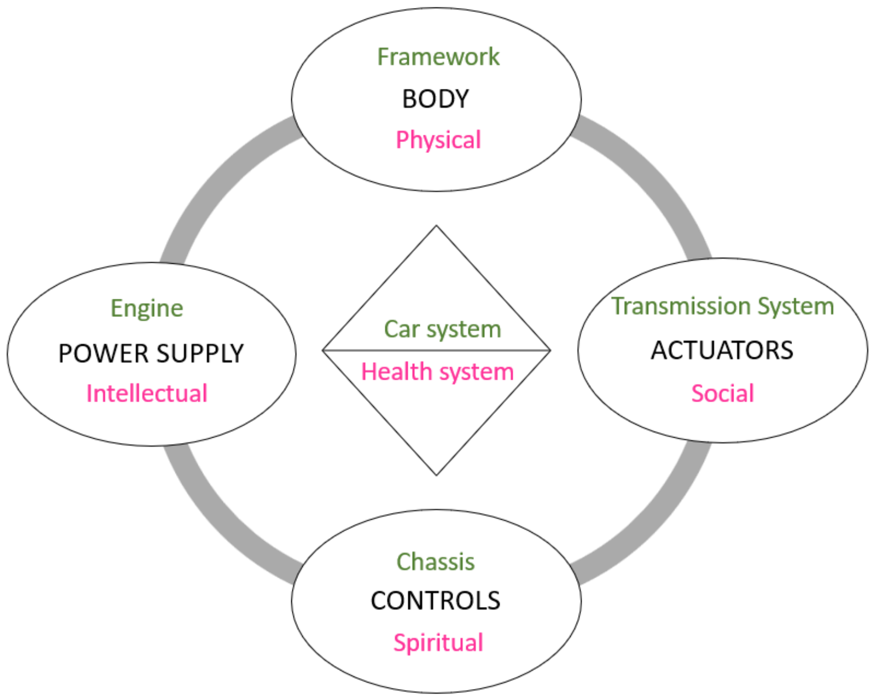


Figure 4.1: Examples of complicated and complex systems

It is important to note that, while the car system is assembled from parts that create the technology of driving in a simple and safe way, in the health system, the dynamic relationship of all the parts introduces the complexity in the system. Therefore, with the same amount of factors, a system can be complicated, but not complex, such as the car system. Thus, the number of elements itself cannot define the level of complexity in a system, because the influence is given by the interactions between these components and their collective impact on the overall system.

Back to mid-1980s, the scientists from the Santa Fe Institute in New Mexico developed the complexity theory, where they proposed that a complex system exhibit a hidden order in its behavior and evolution. [55] A complex system can be defined as a combination of many independent agents that collectively behave as a single unit, unintentionally determining patterns and properties that are not present in any individual component of that system. Thus, the definition of complexity can be interpreted as the definition of happiness. It is important to recognize that happiness is a dynamic and evolving concept, and its attainment may involve a balance of various characteristics in different contexts and stages of life. Similar to happiness, complexity is a multifaceted concept that relies on a set of characteristics to be understood. [84] It represents the nature of the system, including interdependencies, emergent phenomena, and non-linear relationships.

Relating to a system, complexity presents five characteristics according to [84]. First property of complexity is the influence of memory and feedback on the system. This means that the system's present state is affected by its past, and events in one part of the system can affect other parts of it. Moreover, the system responds to the feedback from both internal and external sources. An excellent example of a complex system that demonstrates the influence of memory and feedback is the human brain. A human brain can change action's course when it receives feedback that a risk has been discovered. Another property of complexity is the adaptation of the agents according to their own history. In this case, the human brain can improve its way of thinking based on its own experiences from the past. The next characteristic of complexity is the openness, meaning that the agents interact and respond to their environment. In the case of the human brain, there are numerous external influences that can shape the course of its actions. The human brain constantly receives information from the surrounding environment through sensory inputs such as vision, hearing, touch, taste, and smell. These external stimuli provide the brain with crucial information about the world, and the brain processes and interprets this information to guide its actions and decision-making.

Aside from openness, complexity is characterized by emergence. This characteristic relates to new system conditions that cannot be planned. The human brain exemplifies emergence through its capacity to develop new knowledge and understanding. It can generate ideas and solutions by acquiring new information. Finally, the last property of complexity is dedicated to the mix of ordered and disordered behavior. Complex systems, such as the human brain, exhibit a combination of both structured and unstructured patterns, successes, and failures. The human brain operates in a complex manner where it demonstrates periods of ordered behavior, such as when performing routine tasks. However, the brain also experiences periods of disordered behavior, where it encounters challenges, uncertainties, and failures.

4.2. Sector complexity

Complexity represents a relevant topic in system analysis, with various domains exploring this concept and adopting different strategies based on the system performance with respect to complexity. For example, economic complexity serves as a measure for evaluating a country's economy. The Economic Complexity Index, ECI, is a reference for assessing the complexity of a country's economy. Countries with a higher ECI are considered to possess a more complex economy. Moreover, complexity is measured in an engineering approach as well. Three distinct approaches are commonly employed in this domain. Firstly, system complexity analysis involves assessing the number of components, subsystems, and all their interactions within the system. Secondly, the structural complexity analysis focuses on the physical structure of the system, while the computational complexity analysis evaluates the computational resources required to solve the engineering problems.

From the aviation domain perspective, the complexity concept is a highly important topic, being the subject of numerous papers in the last years. The main topic of the studies is based on enhancing the airspace capacity with respect to the complexity concept. As was mentioned in Section 2.3, the estimation of the capacity within a sector depends on several contributory factors, such as air traffic demand, traffic patterns, vertical movements and so on. For this, an assessment of the complexity of the sector management needs to be evaluated.

Thus, the focus of complexity in the aviation field is mainly on airspace management which is strongly connected to procedures and regulations and also with the administrative members of all airspace providers. In Section 2.2 it was determined that the airspace represents a complex system due to its characteristics. Therefore, if it is taking into consideration a sector as an example of complex system, this system can be described as shown in Figure 4.1. In this case, the body is the sector configuration itself, the actuators are defined by the whole system of procedures and regulations, the controls are the human resources which provide services to the flights, and the power supply is represented by the number of movements in that area.

When analyzing this scenario from a complexity perspective, every block of the chart can be divided into subsystems that interconnect and influence the entire system. The main subsystems include equipment, people, environment, and legislative aspects. Moreover, the main system itself can have its own level of complexity on a global aspect. Managing the airspace of the sector by assessing its capacity, represents a complex problem due to multiple factors. The characteristics of complexity, mentioned earlier in Section 4.1, apply to this scenario. The property of memory and feedback is evident in the reaction of air traffic controllers when a risk has been discovered. The adaption can be observed in the adjustments made to air traffic flows and patterns within the sector to accommodate different traffic situations. Further, the openness characteristic can be described by external factors, namely environment or legislation. Bad weather conditions, natural hazards, or rules implied by the restricted areas are aspects which influence the complexity over a sector. Emergence occurs when air traffic controllers devise efficient solutions to manage air traffic flows within the sector or on a global level. The air traffic controllers implement different solutions in decongesting the air traffic within a sector. These solutions might be an increase in number of delays or various regulations in that specific area. Lastly, the mix of ordered and disordered behavior is based on the direct clearances given by the air traffic controllers to the aircraft. Basically, the flight paths of the aircraft is altered by following the procedures given by the controllers. The aircraft is changing his conventional route in the sector by having a direct one.

As a result, all the elements of the subsystems participate and have an impact on the system itself. The reaction of air traffic controllers, the operational mode of the equipment, the different conditions of the environment, and all the regulations applied to a specific sector are interconnected, creating the sector's behavior. Based on this behavior, different strategies to maximize the capacity can be computed, optimizing the administrative schedule, as well as making the air traffic the most efficient. So, in order to find the best solutions, an assessment of the level of complexity needs to be performed and evaluated in the area of interest.

However, the process of managing complexity in air traffic goes beyond its initial appearance. While each paper has focused on the general concept of complexity, they often approach this concept from different perspectives. Therefore, they all reveal four main areas of complexity research in the field of air traffic. Several studies have concentrated on the link between complexity and the occurrence of operational errors. Notably, the findings conclude that the complexity does not always influence the occurrence of an operational error. According to [56], the complexity within a sector decreases before an error occurrence, which means that air traffic controllers tend to be slightly relaxed or less concentrated on maintaining the separation between aircraft after the complexity within the sector is decreasing. Moreover, the mid-air collision over Überlingen in 2000, happened on a clear and quiet night. However, during the error period, the research discovered an increase in complexity associated with the error.

By measuring complexity, airspace providers can allocate the correct and optimal number of human resources to effectively manage the air traffic flow without disruptions and maximize the capacity. Capacity and complexity are closely intertwined in air traffic management. Enhancing capacity requires a comprehensive understanding of the overall complexity of the system. However, to determine this complexity, it becomes necessary to assess and evaluate the workload of air traffic controllers, who play a critical role in managing the airspace. So, during time, the relationship between complexity and air traffic controllers workload has become very popular in literature. In [74], a Solution Space-Diagram model is used in order to predict the air traffic controller workload with respect to complexity. The study concludes that the complexity represents a source factor of the controller workload by integrating mediating factors, such as environment conditions, operational procedures, and air traffic controllers strategies.

Another main area that complexity has been involved in is the conflict risk. [71] concentrates its study on the influence of the air complexity on the human error probability and, consequently, the risks in ATM, The simulation that the study is using, shows that the number of safety tools alerts correlates with the level of air traffic complexity. So, the higher the level of complexity, the higher the probability of a human error during a conflict. Moreover, complexity plays an important role in the process of decision-making by an air traffic controller. It is certain that the complexity impacts the level of stress of an air traffic controller. Further, this level of stress has a negative impact on the process of decision-making. The consequences are pressure in taking a decision, the late time of reaction, as well as the increased probability of making a wrong decision.

Obviously, over the years a great effort has gone into determining what exactly drives the air traffic complexity. According to the literature, it is also clear that this problem is still being investigated. It is important to note that these studies have been conducted using the technology and operational procedures available during their respective time periods. However, as technology and operational modes evolve, the assessment of complexity may vary. For instance, the implementation of Free Route Airspace represents a solution aimed at reducing flight times and emissions while offering greater flexibility in route planning. However, the level of complexity associated with this operational procedure cannot be determined solely based on past research, as it introduces a different operational paradigm. Most of the studies are done on assessing the complexity on the conventional operational procedures, where the aircraft are following the ATS routes. Thus, an assessment of complexity from a modern perspective, with the current technology and tools, needs to be addressed.

4.3. Air traffic complexity factors

Complexity can be interpreted as a subjective constraint. Let's consider a scenario where a task involves moving a heavy weight from one place to another. A young and strong person might say that the task has low complexity, while an elderly person may consider the task as highly complex. Similarly, complexity is perceived differently in the aviation field. Seasoned and experienced air traffic controllers may coordinate the air traffic within a complex airspace having moderate complexity due to their familiarity with managing challenging situations. In contrast, newly trained controllers may perceive the same task as highly complex due to their lack of exposure and confidence. Thus, having this subjective nature, several factors underlie the complexity concept.

In the past years, a large amount of research has been done in order to determine the factors and influences that make the air traffic situation more or less complex within a sector. While many studies recognize traffic density as a key factor, it is important to note that the concept is often referred to by different terms, such as flight count or static density. However, relying solely on traffic density as a measure of complexity is insufficient in capturing the full range of dynamics and intricacies associated with air traffic behavior in a sector. As an example, let's explore the following scenarios. In Figure 4.2 nine flights across one of the sectors of MUAC airspace are displayed. This represents the traffic density of the airspace at a given moment of time. The aircraft are displayed by the diamonds. The line in front of the diamond represents the position of the aircraft after one minute if the aircraft maintains its current heading, while the dots behind the diamond represent the previous locations of the aircraft. The difference between the green and the white colors is that the green aircraft are on the frequency with the ATC unit. All aircraft have a label which contains different flight information, such as call sign, flight level, and speed.

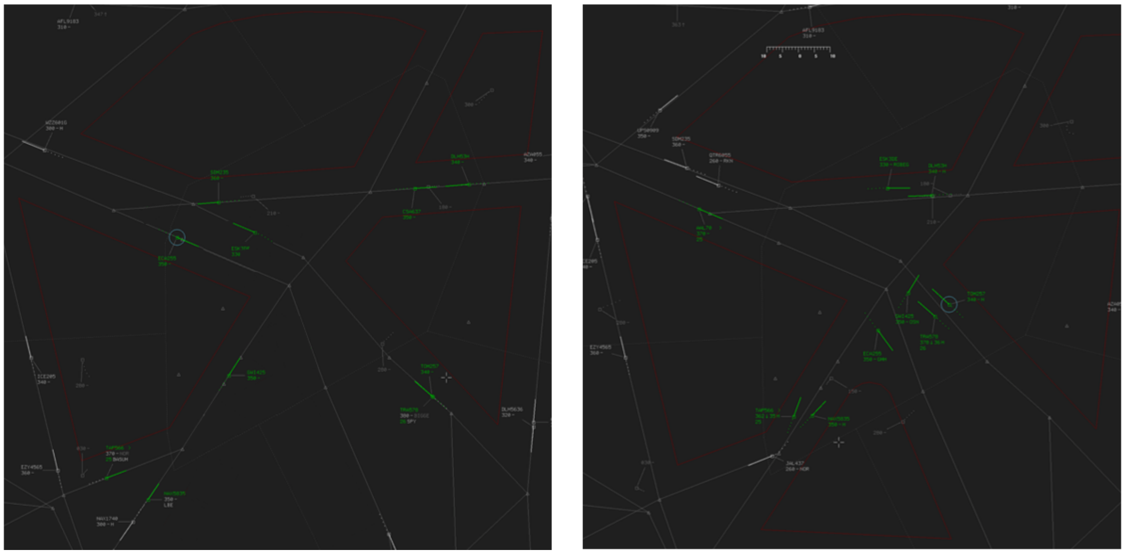


Figure 4.2: Scenario of traffic complexity. Generated by EUROCONTROL simulator software

In Figure 4.2 two scenarios are displayed. On the left-hand side, it can be observed that all the aircraft are flying on the ATS routes, on constant altitudes, speeds and headings. The potential conflicts are well-known, namely the intersection between routes. On the right-hand side, it can be noticed that with the same amount of traffic, the dynamic of the flow is different. It can be seen that some of the aircraft are cleared on direct routes, so the course of their routes are altered. In this situation, the potential conflict may occur on different location than just at the intersection of the routes. Also, it can be noticed that some of the aircraft are changing their flight altitudes, while others are changing their speeds. Furthermore, all these aircraft are flying in an environment where an additional restricted area has been activated. Comparing both scenarios, it can be visibly noticed that the levels of complexity vary even if there is the same traffic density. While on the left-hand side, the air traffic is organized in an ordered manner, on the right-hand side the traffic has a disordered aspect because of different system dynamics.

Therefore, the discovery and identification of the factors that contribute to the creation of the complexity of the airspace has been the focus point of attention in the recent years. While [39] found 33 complexity factors, and [52] found only 12, three large categories of complexity factors can be detected, for example throughout the literature exploration: air traffic situation parameters, properties of the sector, and environment conditions. For each category, several examples of factors will be provided further.

4.3.1. Air traffic situation

Vertical and horizontal movements influence the dynamic behavior of a sector by increasing the level of complexity. A flight consists of a track and a phase. While the track represents the direction of the aircraft, the phase relates to the aircraft's altitude. The track refers to the horizontal projection of the flight, while the phase defines its vertical profile. In other words, an aircraft can be analyzed based on its direction passing the sector or it can be observed how it is maneuvering by turning left or right. The track can be from $0°$ to $360°$. On the other hand, the phase represents the stage of the flight. There are three stages during a flight. The climbing period, where the flight level of the aircraft is increasing, the cruising time, in which the aircraft is maintaining its altitude, and the descending phase, when the flight level of the aircraft is decreasing.

In complexity modelling, these flight interactions, either on horizontal frame or vertical profiles, influence the whole system. In general, when traffic needs to be handled on crossing flows and when the traffic is flying on different levels a more complex scenario exists, than when the traffic maintains a constant behavior. In Figure 4.3 two different scenarios are displayed, where each scenarios has two conditions. In the top left corner, it can be seen that the two aircraft are following a constant altitude. The difference in altitudes between them is 1000 ft, which represents the standard safety measure for the vertical profile. Even if they pass via the same point at the same time, there is no need for them to take action. In contrast, in the top right corner, the same two aircraft are passing via the same point, but they are crossing their flight levels. Here, a potential conflict may happen. In the bottom of Figure 4.3 the two other conditions can be seen where on the left, the aircraft are following the ATS routes by maintaining their track, while on the right, the aircraft receive a clearance of direct routes, so their tracks are changed. This change of track may be a solution to a potential conflict, so in this case the level of complexity decrease. However, changing the flight path has a consequence of moving the potential conflict to another place towards another timestamp.

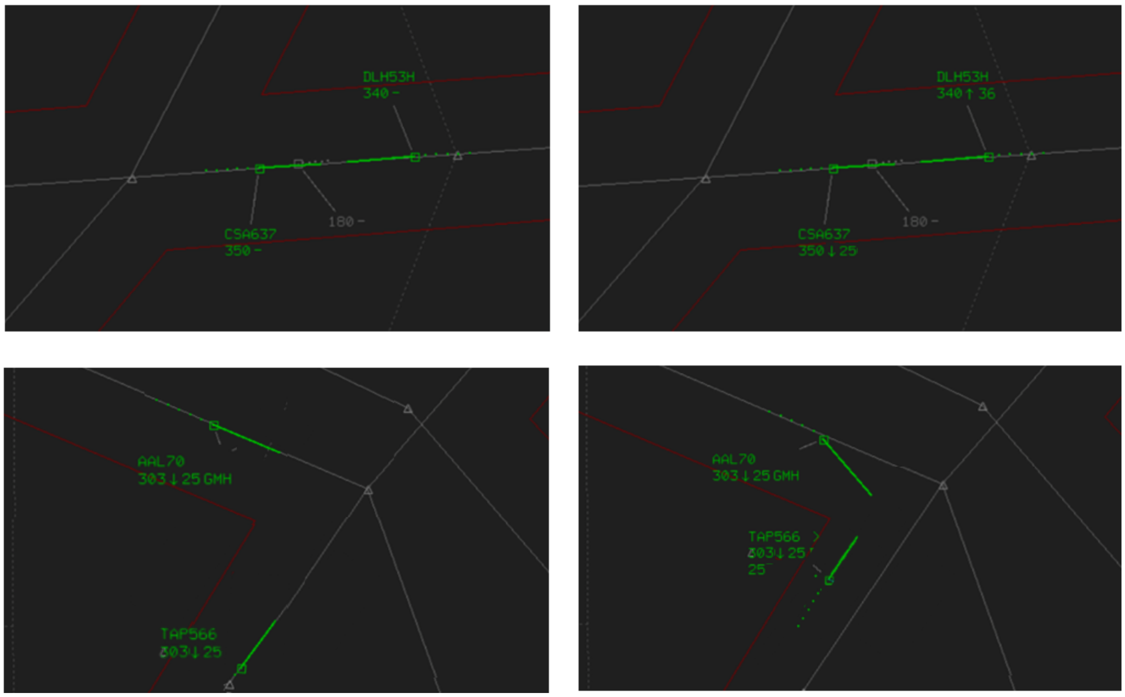


Figure 4.3: Scenarios of flight interactions. Generated by EUROCONTROL simulator software

In Section 2.3 the standard separation on the en-route environment was mentioned. Another factor that falls under this category is the presence of proximate aircraft pairs. Basically, this factors indicates the likelihood of close proximity flight by the aircraft. When two aircraft enter each other's separation cylinder, which has a radius of 10 NM and extends 2000 ft vertically, they form a proximate pair. This proximate pair can be split into two classes. The first class consists of opposite direction proximate pairs, where the aircraft are flying in opposite directions, towards each other. The second class is formed by the speed of the aircraft. In this case, the aircraft are not oriented in an opposite direction, but rather following each other, with the trailing aircraft having a higher speed than the leading aircraft. The first class is displayed in Figure 4.4, and the second one is shown in Figure 4.5. The variability in aircraft speeds can be attributed to various factors such as regulatory requirements, operational efficiency, and aircraft type. Therefore, the traffic mix may impose a constraint in measuring the complexity.

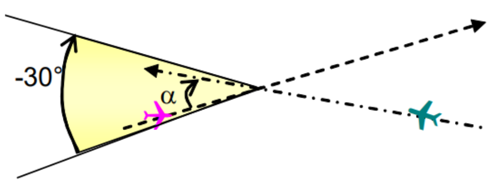


Figure 4.4: Proximate pairs: opposite direction [39]

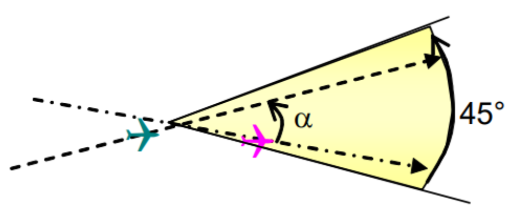


Figure 4.5: Proximate pairs: along track [39]

Moreover, the flights entering the sector represent another important factor that contributes to the complexity of air traffic management. When pilots enters a sector, they are required to establish communication with the air traffic controller responsible for that sector. From that point forward, the air traffic controller assumes control and responsibility for managing the aircraft's movement within the sector. If the entering rate of flights within a sector in a given period of time is high, the air traffic controller may experience an increased workload and a higher level of complexity in managing the traffic. For example, it is estimated that five aircraft entire the sector in a 30 minute time window. If these five aircraft enter the sector at the start of the time-frame, the level of complexity increases more than if the same number of flights are distributed over a larger time frame.

4.3.2. Sector configuration

The configuration of a sector can significantly impact the complexity of air traffic. The way in which a sector is divided, whether it is in terms of its size, shape, or boundaries, can influence the management of air traffic within the sector. For example, larger sectors may require more extensive coordination and communication among controllers. Additionally, poorly designed or overlapping sector boundaries can introduce complexity, as they may result in unclear responsibilities for aircraft or increased coordination requirements between controllers.

The routes network within this configuration plays an important role in identifying the level of complexity. While the number of routes alone does not directly impact complexity, the number of intersections between these airways can definitely increase the number of challenges in the sector. In other words, when two routes intersect, the air traffic controller responsible in that sector must actively monitor the traffic to ensure the standard level of safety. As was discussed in Section 2.2, intersections between routes create potential conflict points where the trajectories of the aircraft can converge. The more intersecting airways there are, the higher the likelihood of these conflict points arising, increasing the complexity of managing traffic in the sector.

Below en-route sectors aerodromes may exist which can impact the dynamics of the flow within the sector. When an aerodrome is located below a sector, vertical movements of aircraft become necessary as they ascend after takeoff or descend in preparation for landing. Moreover, each aerodromes requires a designated airspace volume for arrivals or departures, which results in configuring fixed enter and exit points within the en-route sector. This introduces constraints and complexities in managing the air traffic, because air traffic controllers must ensure proper coordination and sequencing of aircraft to facilitate their transition from en-route environment to the terminal area. However, the ground operations, airport capacity, and airport resources may affect the traffic volume on the en-route environment. If an aerodrome experiences congestion, delays or increased waiting times for aircraft may appear. These delays have an impact on the whole air traffic flow within the sector.

Based on the sector volume, the flight time within a sector may vary. Depending on the route within the sector, aircraft may have a shorter or longer flight time in the space volume. Usually, for a longer sector flight time, sustained attention, coordination, and decision-making are required. Thus, the more an aircraft stays on the sector frequency, the more workload is given to the air traffic controller. Moreover, a longer average sector flight time can result in a higher density of aircraft within the sector at any given time. However, a short period of flight within the sector may not be optimal as well, because a short-term transiting aircraft enters the frequency of the sector and it requires a handover to the next sector, which increases the number of procedures for the air traffic controllers.

4.3.3. Environment conditions

The level of complexity may be interpreted differently from one air traffic controller to another. The interpretation is based on their knowledge, experience, and training on managing the air traffic in different scenarios within the sector. Experienced controllers possess a higher level of situational awareness and can anticipate traffic flows and potential conflicts faster than an air traffic controller which just started operating the specific sector area. The experience allows to handle complex situations more efficiently and effectively. In addition to this, the cognitive nature of the ATC represents the main reason for the nonlinear interactions between complexity factors and different responses to the same complex system. This cognitive complexities relies on the perception of the air traffic controllers and the air traffic situation recognition.

The presence of restricted areas introduces additional constraints and considerations for air traffic controllers. Even though it is talking about military exercises or bad weather conditions, this restricted areas alter the air traffic resulting in rerouting or diversion of flights. When a restricted area is active or temporarily expanded, aircraft may need to deviate from their planned routes to avoid these areas. This rerouting process requires controllers to assess the impact on traffic flow, communicate with affected aircraft, and coordinate with adjacent sectors or air traffic control units to ensure a smooth transition. Furthermore, the presence of restricted areas can lead to a traffic concentration in specific areas or routes, as aircraft are constrained to navigate around these restricted zones.

4.4. Air traffic complexity metrics

Measuring complexity plays a vital role in evaluating the performance and efficiency of a system. It may enable the identification of areas where complexity can be reduced or streamlined, leading to a better performance of the system. Moreover, by assessing complexity, opportunities for optimization can be identified and informed decisions, to ensure the system operates at its best, can be made. Therefore, in this section, several complexity metrics are described.

Complexity metrics represent quantitative measures used to assess the level of complexity within a system. These metrics provide a structured approach to understand and analyze the interconnected nature of the system. The scope of these metrics is to capture various aspects of complexity and to explain the system behavior. Considering an air sector as a complex system, where the agents are the flights within this specific sector, the use of complexity metrics allows to detect its behavior, performance, and management. By applying these metrics, it becomes possible to identify and evaluate potential vulnerabilities of the sector. Researchers implement different metrics to facilitate the sector optimization. These metrics are presented further in this report.

4.4.1. Dynamic density

It was determined that despite of the number of aircraft per sector, other air traffic indicators are relevant in assessing the complexity within a sector. These indicators are related to the sector configuration, flow characteristics, and environment conditions. More than that, these indicators are classified in static and dynamic air traffic characteristics. Static air traffic characteristics are fixed for a sector and are determined by spatial and physical attributes such as airspace configuration, the number of airways, the number of routes crossings, and also the number of navigation aids. On the other hand, dynamic air traffic characteristics are variable and change over time. They are influenced by various factors such as the number of aircraft present in the sector, restricted areas due to weather or military exercises, aircraft separation requirements, conflicts rates, mix of aircraft types, and flow restrictions. These dynamic factors introduce variability and complexity into the air traffic system, as they constantly fluctuate and interact with each other in a nonlinear manner.

Dynamic density represents an aggregate measure that captures the complexity of air traffic by combining multiple static and dynamic characteristics. It serves as a metric which takes into account both subjective and objective workload measurements. Dynamic density can be defined as a collective effort of all factors that contribute to sector-level complexity at any point in time. [74] Being an aggregate metric, different dynamic density measures are proposed in the literature. In 1999 a partnership between three big entities was formed in order to research this metric. By that time, 65 qualified air traffic controllers were involved in the measure. The air traffic controllers needed to answer several questionnaires related to the factors that may affect their performance. Based on these results, each organization came up with its own model based on en-route air traffic controllers working live traffic data. The similarity of all the models is that the formulation of the metric is given by Equation 4.1. [74]

$$DD = \sum_{i=1}^{n} F_i W_i \tag{4.1}$$

In Equation 4.1 dynamic density, noted by DD, is a summation of n complexity factors, F_i, and its corresponding weight, represented by W_i. The values of the weights are gathered from regression methods and they are compared to subjective workload ratings. In order to determine the dynamic density for different sectors, the weights need to be recomputed and re-validated for each scenario. The shortcoming of this is that the metric can only be performed on scenarios that do not differ too much from the baseline scenario.

However, in the Equation 4.1, the number n represents the number of complexity factors that are integrated in the model. This number can vary from one model to another. For example, FAA W.J.H. Technical Center, WJHTC, integrates nine variables in the model, while the Metron Aviation organization proposed the calculation with ten variables. Furthermore, NASA Research Center explored two versions of the models, one with eight variables and the other one with 16 variables. The list of all the complexity factors can be found in [39].

In conclusion, dynamic density is an aggregate metric which is strongly linked to the subjective activities of ATC. It can be assumed that the dynamic density is a controller-dependent method since the measure takes into account the perceptions of the air traffic controllers with respect to their performance in a complex situation. By the end of year 2000, EUROCONTROL launched a major project related to this interdependency between ATC workload and complexity. The project's assumption is that the complexity drives controller workload, and that the capacity is limited by the workload. Thus, the main objective of the project is to describe the impact of the factors, which create workload, on capacity and complexity. The approach described in [25] consists of developing a metric based on both static and dynamic data. The model is evaluated on the air traffic flows which are crossing MUAC airspace and it proves quantitative measurements of different factors along the MUAC sector areas. For example, in the Brussels sector group, a sector change has been done in mid-2004 caused by the hotspot around the REMBA navaid. This place had a high level of complexity due to the high rate of incidents occurrences. An analysis of this change was performed by COCA model. As a result, it was demonstrated that the sector in which the REMBA navaid is located, still remains a high complexity sector, but the values of complexity due to this change have been reduced significantly.

4.4.2. Interval Complexity

A time-smoothed version of the Dynamic Density metric is the Interval Complexity, IC, metric. This metric was introduced in [38] and it estimates the workload of air traffic controllers within a sector. It is defined as the average of a linear combination of different complexity factors over a 5-10 minutes time window. In order to create a complexity solver within a sector, [38] performs an Optimisation Programming Language on the ATC centre from Maastricht. The algorithm computes the Interval Complexity metric, using this metric is calculated by using Equation 4.2.

$$IC(s,m,K,L) = \frac{\sum_{i=0}^{k} MC(s,m+i,L)}{k+1} \tag{4.2}$$

where the IC of a sector s over an interval $[m \dots m+kL]$ is the average of its moment complexities at the sampled moments. The constant k is the smoothing degree which in the study is equal to $k=2$ and L is the time step between the sampled moments. $MC(s,m+i,L)$ represents the moment complexity which is computed by using Equation 4.3. [38]

$$MC(s,m) = (w_{sec}N_{sec} + w_{cd}N_{cd} + w_{nsb}N_{nsb})S_{norm} \tag{4.3}$$

w_{sec}, w_{cd}, w_{nsb} are experimentally determined weights, S_{norm} characterises the structure of the sector, N_{sec} represents the number of flights in the sector at moment m, N_{cd} represents the number of flights in the sector that are non-level at moment m, and N_{nsb} is defined as the number of flights that are beyond their entry or exit point into the sector s. Non-level flights are the flights which do not maintain a constant altitude within a sector. The study concludes with a result of significant complexity reductions and re-balancing.

4.4.3. Solution Space Diagram Method

The level of safety within a sector is very important, especially when dealing with high complexity. A high level of complexity can potentially lead to safety issues and violations of separation. These problems can be caused by the heavy workload experienced by the air traffic controllers. Therefore, one metric that analyzes the available solution space within a sector is represented by the Solution Space Diagram approach, SSD. This metric offers an objective and scenario-independent perspective compared to traffic density, for example. Initially, the SSD approach was used in order to show potential future trajectories that could result in separation violation from a pilot's viewpoint. However, this approach was later expanded to the air traffic controller's perspective. The SSD metric serves as a proactive tool for preventing conflicts by identifying situations where heading turns or velocity changes of an aircraft may potentially lead to conflicts with other aircraft. In the present day, the SSD is also used to monitor the impact of aircraft proximity and the number of streams on air traffic controller workload. [74] mentions that the SSD approach can be used in order to mitigate controllers' workload in a situation of increased traffic levels.

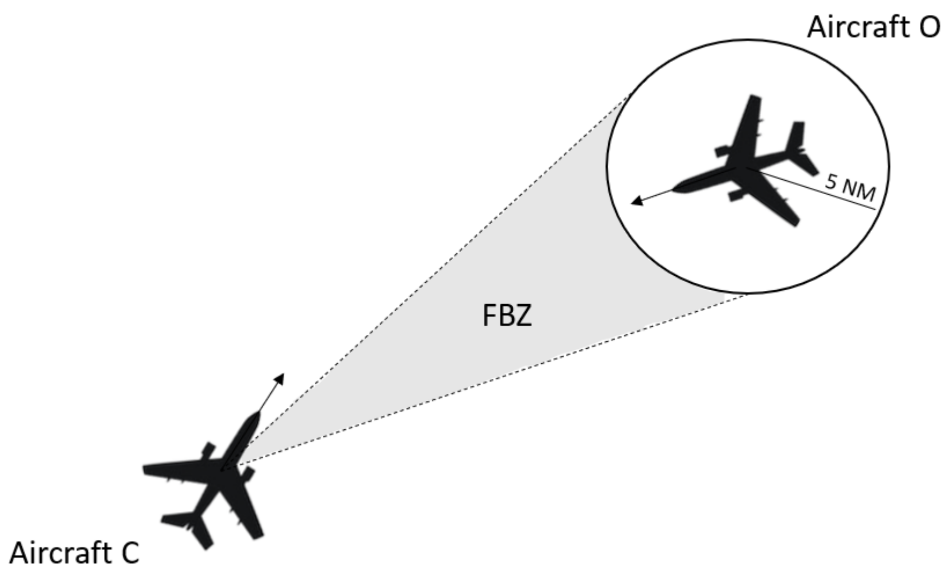


Figure 4.6: Plan view of conflict and the corresponding FBZ. Adapted after [72]

In order to present the SSD, a Forbidden Beam Zone, FBZ, needs to be determined. Let's consider two aircraft positioned as in Figure 4.6. The *aircraft C* is the controlled aircraft and the *aircraft O* is the observed one. Each aircraft has a protection zone. This zone is computed according to the standard separation measurements. In Figure 4.6 the protected zone of the observed aircraft, which is represented with a circle with a 5 NM radius is displayed. The violation of this area is interpreted as a conflict or loss of separation. However, the area between the two tangent lines which connect the protected zone of the observed aircraft with the center of the controlled aircraft is called FBZ. This area is marked by the gray color. An example of SSD from the controlled aircraft's perspective is shown in Figure 4.7. Figure 4.7 illustrates a SSD of an aircraft, with three other aircraft within the area. The light green area indicates the directions and speed range of the controlled aircraft in which there is no conflict, while the red area defines all possible velocity vectors for the controlled aircraft that could lead to future separation violation. The inner and outer circles are the velocity limits of the controlled aircraft. In order to measure the complexity with this approach, the complexity score is determined by the ratio of the red area over the total area between V_{min} and V_{max}.

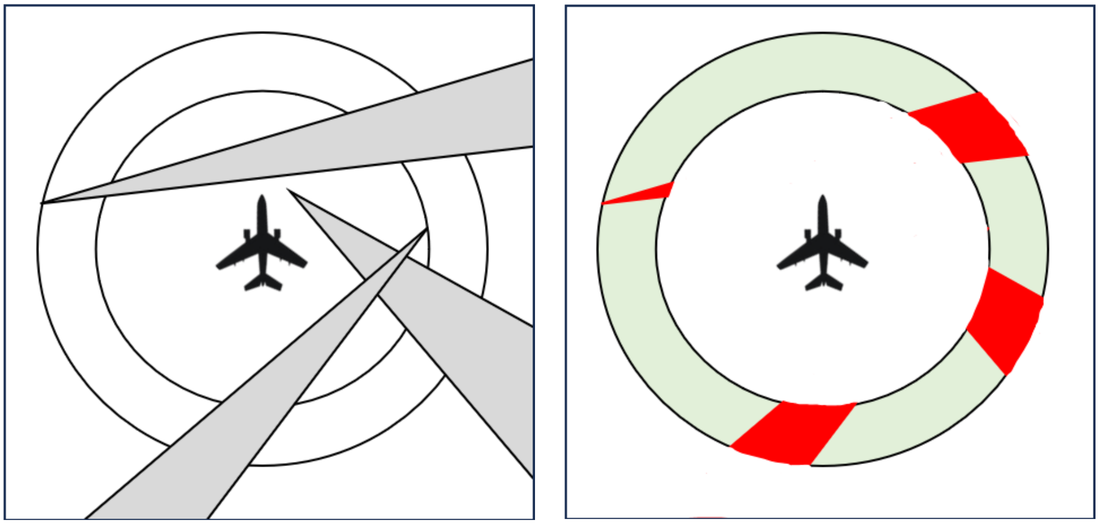


Figure 4.7: Example of SSD unsafe area. On the left-hand side: SSD with multiple no-go beams. On the right-hand side: The unsafe area. Adapted after [72]

Several studies have utilized the SSD approach to measure complexity within air traffic sectors. For example, [57] employed a simplified version of the SSD method and obtained promising findings. The results show that the average percentage is between $7-15\%$, where 100% represents the incapability of the aircraft to turn any heading anymore. Another result can be observed in [74]. Using a SSD model, the study observes that a higher intercept angle, results in a smaller complexity metric. However, this condition is only true when the observed aircraft has a route length larger than or equal to the route length of the controlled aircraft. [72] addresses the question whether the SSD is a good measure of sector complexity. Despite the limitations of the model, such as assumptions and simplifications, the approach proves to be a valuable metric for assessing complexity within the sector. However, it should be noted that the assumption of fixed flight levels in the simulations makes the metric less realistic.

4.4.4. Fractal Dimension

Similar with Dynamic Density, Fractal Dimension is an aggregate metric. However, this metric is independent of sectorization and it is used to measure the geometrical complexity of a traffic pattern from different operational concepts. In the context of complexity measurement, the fractal dimension provides a way to characterize the self-similarity or irregularity of a system. Complex systems often exhibit fractal properties, where patterns repeat at different scales. Higher fractal dimensions indicate greater complexity, as the structure exhibits more intricate and detailed patterns across different scales. Lower fractal dimensions suggest smoother or simpler structures with less self-similarity.

The fractal dimension is typically determined by using mathematical algorithms, such as the box-counting method. This method was exploited in [59]. The box-count method was applied in order to approximate the fractal dimension for different flight scenarios in the USA. Performing a conflict analysis, the study reveals that the fractal dimension increases with the transition to the free flight operations, and this leads to a reduction in the expected number of conflicts. However, this finding is applied in en-route sectors. In the transition sectors, it was determined that the conflicts increase. As a consequence, it can be noted that the free routing scenarios may have contrasting effects on the dimensionality of air traffic. While it increases dimensionality en-route, it decreases the dimensionality in the transition sectors. Even if the balance of these factors results in a constant number of conflicts, the reality is that the conflicts increase in transition sectors and decrease in en-route environment.

4.4.5. Input-Output Approach

In order to identify problematic elements of the sector boundaries, the complexity map is proposed as a complexity metric. A complexity map is defined in terms of the control effort needed to avoid the occurrence of conflicts when a new aircraft enters the airspace. In [69], the airspace looks like an input-output system. The closed-loop system of the airspace can be seen in Figure 4.8.

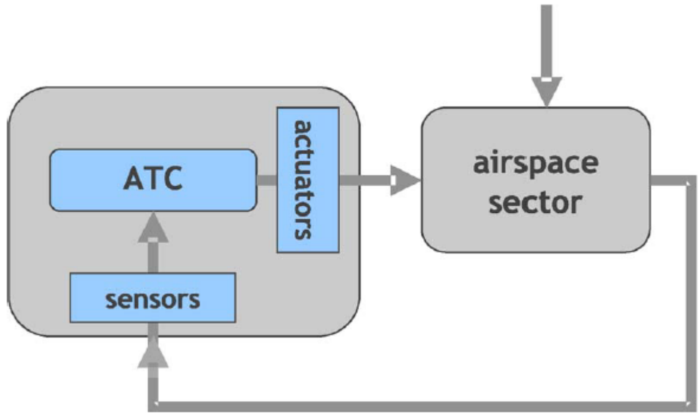


Figure 4.8: Airspace closed-loop system [69]

While the controlled system is represented by the sector area, the feedback controlled is defined as Air Traffic Control. ATC interacts with the control system via sensing and actuating interfaces. The input to the closed-loop system is represented by the additional incoming traffic from the neighboring sectors. The behavior of the input data is provided to the ATC by sensors, such as the Communications, Navigation and Surveillance, CNS, systems. The actuators are represented by the ATC commands, such as speed, altitude or heading changes, to the pilots. The output of the system is determined by the deviation observed in the flight paths of the aircraft already present in the traffic. These deviations occur as a result of adjustments made by the feedback controller to the original flight plans, which were initially issued to ensure the safe integration of the incoming aircraft.

In order to assess the overall amount of corrective actions needed to recover a conflict condition, a complexity map is created as a function of the entering position and bearing of the incoming aircraft. In other words, when an additional aircraft enters the sector, the presence or absence of conflicts among the existing aircraft determines the required control activity. The control activity is considered to be minimal or zero when there is an indication of a conflict-free condition. In contrast, if multiple aircraft within the sector need to be given new instructions, such as heading or speed commands, to avoid conflicts with the incoming aircraft, the control activity is considered to be high. Therefore, the overall amount of corrective actions needed to restore a conflict-free condition serves as a measure of the air traffic complexity. Higher complexity is associated with a greater number of corrective actions required to resolve conflicts and maintain safe separation between aircraft.

4.4.6. Intrinsic Complexity Metrics

Several research papers do not include the cause-effect relation between complexity and workload. Therefore, they present different approaches of monitoring the complexity within sectors in their studies. In literature these controller independent methods are called Intrinsic Complexity Metrics. This leads to the creation of metrics with respect to air traffic distribution in the airspace without integrating the ATC workload. For this purpose, the level of disorder and air traffic distribution can be captured without taking into consideration their effect on the workload. Delving more into the intricacy of the complexity metrics, these metrics are computed by using linear and non-linear dynamical systems. Based on the linear dynamical system, the metrics can measure the local disorder of a set of trajectories in the proximity of a specific aircraft at a given time. Basically, the linear dynamical system models the aircraft trajectories, which further helps to identify different structures of organization of the aircraft speed vectors, including translation, divergence, convergence or a combination of them.

As a result of the dynamical system is a vector field which is described by the following linear equation. [15]

$$\dot{\vec{X}} = A\vec{X} + \vec{B} \tag{4.4}$$

In Equation 4.4, $\vec{X}$ represents the state vector of the system expressed as in Equation 4.5. The $\vec{B}$ defines the behavior of the vector field, while the eigenvalues of matrix A control the evolution of the system.

$$\vec{X} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{4.5}$$

For this purpose, a set of data is extracted from radar trackers, namely positions and speeds of aircraft. Thus, in order to create the vector field, for each aircraft is associated a position vector $\vec{X}_i$ and a speed vector $\vec{V}_i$, where i defines the moment of time. The vectors $\vec{X}_i$ and $\vec{V}_i$ are characterized by Equation 4.6.

$$\vec{X}_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \quad \vec{V}_i = \begin{bmatrix} v_{x_i} \\ v_{y_i} \\ v_{z_i} \end{bmatrix} \tag{4.6}$$

Therefore, the vector field can be computed. For a better understanding, a vector field is represented in Figure 4.9.

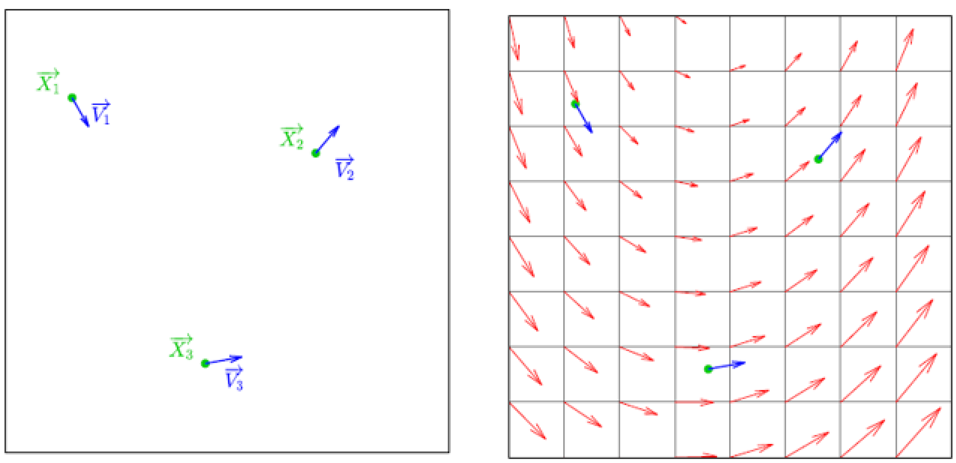


Figure 4.9: Example of vector field computation with three aircraft [18]

Further, the eigenvalues of matrix A are complex numbers which give the mode of the system. Based on these values, the dynamical system can evolve in contraction, expansion, rotation or a combination of those three modes.

Having the linear model, Lyapunov Exponents can be estimated. This metric is a measure of sensitivity of the underlying vector field. [57] and [16] explore this metric in their studies. The Lyapunov Exponents expose the area in which the underlying dynamical system is organized. Basically, this metric allows to identify identify the traffic pattern if it is fully organized or not. A fully organized traffic pattern means that the traffic is very predictable and very comfortable to address by a controller. Thus, Lyapunov Exponents indicate the level of order and disorder of a system. [16] proposes a Lyapunov Exponent model, where the trajectory of the dynamical system is described by Equation 4.7.

$$\gamma(t, \vec{x_0}) = \vec{x_0} + \int_0^t \vec{f}(u, \gamma(u, \vec{x}))du \tag{4.7}$$

where γ is the trajectory, $\vec{x_0}$ is the initial point, and $\vec{f}$ is the vector field. If this dynamical system is perturbed with $\vec{\epsilon}$, the trajectory can be expressed as in Equation 4.8.

$$\gamma(t, \vec{x_0} + \vec{\epsilon}) = \gamma(t, \vec{x_0}) + \nabla_{\vec{x}}\vec{f}(\gamma(t, \vec{x}))\vec{\epsilon} + o(\|\vec{\epsilon}\|) \tag{4.8}$$

Thus, the divergence of the trajectory γ in a three dimensional environment is estimated by calculating the differential equation Equation 4.9.

$$\frac{dA(t)}{dt} = \nabla f A(t) \tag{4.9}$$

where A is the matrix which corresponds to the divergence of the flow associated to the principal coordinate axis. Finally, the Lyapunov Exponents are expressed as a negative mean of the logarithms of the singular values of the single value decomposition. The expression for these exponents is given by Equation 4.10.

$$LE(\vec{x}) = -\frac{\sum_{i=1}^{i=3} log\lambda_i(\vec{x})}{3} \tag{4.10}$$

In Equation 4.10 λ_i represents the eigenvalues of the matrix A. In conclusion, the complexity score of the specific area is described by summing all the Lyapunov Exponents. The meaning of these exponents is as follows. The higher the value of this metric, the higher the level of complexity is in this sector. Furthermore, the metric can have negative values, which means that the distance between aircraft will increase. In contrast, a positive value implies that the relative distance will decrease.

Another intrinsic measure of complexity can be considered is Kolmogorov entropy. This metric may describe the traffic flow organization. [17] measures the complexity of french traffic by identifying the traffic pattern organization. The study uses two different sectors. Each sector is simulated using both operational methods, standard and direct routes. The results of the study reflects that in one sector the direct route assignment will decrease the complexity, while in the other sector, this operational mode will increase the complexity.

4.5. Overview of MUAC traffic complexity

In the previous chapters, insights into the environment and operational procedures at MUAC were described. The focus of this section is shifted towards exploring the traffic complexity within MUAC. An analysis substantiating the reason of being considered one of the most complex airspace areas globally is presented in this part.

Taking into consideration the characteristics presented in Section 4.1, MUAC is considered a complex system. Its characteristics define the properties of a complex system. For example, the influence of memory and feedback is present in the airspace area. Feedback loops are an inherent part of MUAC airspace. Thus, decisions and actions taken by air traffic controllers and pilots influence the behavior of the system. Moreover, MUAC has the ability to adapt and respond to changing conditions. The system continuously monitors and analyzes various inputs, such as traffic flow, weather, and airspace restrictions, and adjusts its operations accordingly. This adaptive capacity is an essential characteristic of complex systems.

The interconnectedness characteristic is presented in MUAC airspace as well. MUAC is interconnected with other air traffic control centers, airports, and various stakeholders in the aviation industry. Additionally, the interactions among aircraft, air traffic controllers, weather conditions, and other factors within the airspace lead to an emergent behavior. Finally, the nonlinearity property of a complex system is present. The behavior of air traffic within the MUAC sector is nonlinear, meaning that small changes or disruptions in one area can have ripple effects throughout the system. This nonlinear behavior adds to the complexity of managing and predicting air traffic patterns.

Presenting all these characteristics of MUAC airspace, it can be said that MUAC operates as a complex system and therefore it is essential to measure the level of complexity within this airspace.

Moreover, there are several aspects and characteristics of these sector groups which amplify the level of complexity. For example, the geographical position of MUAC plays a significant role in determining the complexity of the traffic. MUAC is located in the heart of Europe, and it is responsible for managing the traffic among major European airports. Having such airports below the airspace increases the vertical movements which amplifies the level of complexity within the airspace. [39] analyzed these vertical movements for all three sector groups. In order to estimate the rate of non-level flights, four categories of flights are defined. Internal flights represent those flights which have departed and landed within the sector groups' geographical boundaries. In contrast, the overflights are the flights that have passed through the sector group without departing or landing in one of the airports located below the airspace. The last two categories are the landing and departing flights, which are defined by those flights which have either departed or landed at aerodromes located in one of the sector groups.

The analysis reveals that the distribution of flight types which create vertical movements within MUAC sectors does not exceed 20%. The reason of this percentage is that MUAC primarily handles the traffic from upper airspace, which consists mostly of overflights.

Apart from vertical movements, MUAC manages a large airspace region, which can contribute to the level of complexity. This larger size makes the average time of flying within the sector bigger. According to Section 4.3, it can be said that the larger the amount of time spent in the sector, the higher the workload of air traffic controllers will become. The mixture of aircraft types represents another factor present in MUAC airspace areas. Starting from 2020, MUAC applies the Flexible Use of Airspace principle. [34] This concept refers to the fact that the airspace is not classified as military or civilian, but it is considered a national asset. In other words, the military and civil aircraft are operating the same airspace. This implementation is a consequence of the existence of multiple restricted areas within the airspace.

Regarding the air traffic situation within MUAC sectors, it can be mentioned that the main flows from Europe are passing through this upper airspace, making the flight interactions more complex. At the REMBA navaid, which is located in the Brussels sector group, a hotspot of incidents has been identified. Around this point, the number of incidents has increased in the past years. However, in order to reduce the conflict rate, MUAC has been implemented a new strategy. The strategy consisted of creating new sectors, where the complexity may be divided over these sectors. As a part of this strategy, it was noticed that this change reduced the incidents occurrences rate and also increased the capacity within the sector group.

Since the MUAC airspace is a complex airspace with multiple factors that may influence the system behavior, several studies have been done on determining the level of complexity within this airspace. These studies aim to understand and quantify the factors that contribute to the complexity of air traffic operations in the region. As was mentioned in Section 4.4, one of the biggest projects related to the traffic complexity around MUAC airspace area is the Complexity and Capacity, COCA, project. This project was launched by EUROCONTROL in 2000 [25], and it aims to analyze the relationship between capacity and complexity using static and dynamic data. The project evaluates operational complexity of the air traffic flows which are crossing this airspace, as well as the characteristics of the environment.

MUAC regularly conducts assessments and analyses of air traffic complexity within its airspace. These assessments involve the examination of factors such as traffic volume, sector configuration, route network, weather conditions, and controller workload. The findings from these assessments help in identifying trends, patterns, and potential areas for improvement in managing air traffic complexity. Moreover, MUAC collaborates with other aviation stakeholders, research institutions, and universities to undertake research projects related to air traffic complexity. These projects explore topics such as the impact of new technologies, airspace design, traffic flow management, and human factors on complexity. The research findings contribute to the development of strategies and solutions for enhancing the efficiency and safety of air traffic operations.

4.6. Summary

This chapter delves into the concept of complexity and its significance in the aviation field, particularly within the context of the en-route sector. The chapter starts by providing a general overview of complexity, acknowledging its multifaceted nature and the numerous factors that contribute to its definition. In Section 4.1 the difference between complexity and complicated is described. The example that is given in the chapter compares a car system with the general health system. It is important to understand that even though the car system is assembled from well-known and understandable parts, this system cannot be perceived as complex as the health system is. The health system represents a complex system due to the interconnections of all the agents within the system and their impact on internal and external level. For a system to become a complex system, some characteristics must be meet. Among these characteristics, the influence of memory and feedback, the adaptive character, the openness, the emergence property, and also the mix of ordered and disordered behavior can be found.

Further, Section 4.2 centers the complexity concept within the aviation domain, specifically with respect to en-route sectors. Starting from the fact that the airspace area represents a complex system, many research papers put an effort in determining what exactly drives the air traffic complexity. Therefore, Section 4.3 is dedicated to air traffic complexity factors. Among the complete list of complexity factors, three main categories are presented in this section, namely the factors dedicated to the air traffic situation, those which can be described by the environment conditions, and also those which can be derived from the sector configuration. Among all the complexity factors, traffic density seems to be the most popular factor integrated in literature. However, it needs to be noted that the level of complexity may vary between situations even if there is the same traffic density.

Knowing the factors that contribute to complexity, Section 4.4 delves in computing these factors and creating useful metrics. In this section six complexity metrics are presented. Dynamic Density is the first metric described. This metric uses static and dynamic data and represents a summation of n complexity factors and their corresponding weight. One of the most important projects done on complexity is the COCA project where the impact of several factors on capacity and complexity within MUAC sector is described. Similar to Dynamic Density is Interval Complexity which estimates the workload of air traffic controller within a sector.

The level of safety within a sector is very important, especially when dealing with high complexity. Thus, Solution Space Diagram Method is a metric which can monitor and prevent conflicts by identifying situations where heading turns or velocity changes of an aircraft may potentially lead to conflicts with other aircraft. Another metric defined in this section is the Fractal Dimension, which provides a way to characterize the self-similarity of the system. This metric analyzes different operational concepts, such as scenarios with conventional ATS routes or scenarios based on free routing technology.

Input-Output Approach translates the complex system in a closed-loop system where the input represent the new aircraft entering the sector and the output is determined by the deviation observed in flight paths of the aircraft already present in the system. The last metric that was described in the this part of the report is a metric which is controller and space independent. With intrinsic complexity metrics, the level of disorder and the air traffic distribution can be captured without taking into consideration the ATC workload. In this category Lyapunov Exponents and the Kolmogorov entropy were discussed.

The chapter ends with Section 4.5, where the complexity characteristics of MUAC airspace are presented. It is determined at the beginning of the section that the airspace under MUAC responsibility is a complex system. Furthermore, it is explained why this airspace is considered the most complex en-route airspace in Europe. The complexity characteristic is determined by the presence of vertical movements, Flexible Use of Airspace, and conflict rates. Also, it may depend on size of the airspace, and its strategical geographical position as well.

5 Findings and conclusions

This chapter is dedicated to the exploration of the main findings and conclusions of this literature study. The purpose of this chapter is to summarize and analyze the data collected in the context of existing literature and theoretical frameworks. The examination of previous research delves the report in identifying any existing gaps in knowledge, which can serve as a foundation for future investigations.

For several years, a constant increase in air traffic has induced more and more congestion in the control sectors. Two strategies can be applied to solve challenging problem. The first strategy involves modifying the airspace to accommodate the rising demand, while the second strategy focuses on adjusting the demand to the existing airspace structure. This report explores the possible solutions based on the first strategy, which entails enhancing sector capacity through the implementation of Free Route Airspace.

The implementation of Free Route Airspace aims to address the limitations of the traditional ATS route network by offering greater flexibility in route selection. While FRA allows aircraft to choose more direct routes, it can result in fixed routes becoming less prominent. As a consequence, the predictability aspect of aircraft routing may be compromised. Conflict areas in the airspace may become harder to identify, leading to the emergence of less visible hotspots. This aspect influences more factors within the ATM system, including the workload of the air traffic controllers and compromising the level of safety over the sector. One of the primary advantages of implementing FRA is the potential to accommodate a larger number of aircraft within a given airspace, thereby enhancing overall capacity. However, the increased flexibility in routing may also introduce challenges related to identifying and managing conflicts effectively, which lead to a higher degree of complexity within the airspace. Thus, this raises an important examination on how the implementation of FRA truly serve as a solution to enhance airspace capacity.

Therefore, the answer to the aforementioned question may be divided into two main parts. The first part is traffic related, focusing on how the traffic is behaving and how the FRA impacts the operational procedures with respect to maintaining an optimum level of traffic complexity. On the other hand, the second part is concerned with the environmental implications of implementing FRA. As the implementation aims to accommodate the projected growth in air traffic by increasing the number of aircraft in the sky, it becomes essential to assess how this expansion aligns with minimizing the overall environmental impact. The analysis for the first part is included under the following research question:

How does the implementation of Free Route Airspace, FRA, impact sector capacity when assessed using different traffic complexity metrics?

As discussed in section Section 3.2, the implementation of Free Route Airspace brings numerous benefits to the air traffic management system. These benefits include shorter routes, cost savings in fuel consumption, and improved environmental sustainability. FRA has also demonstrated a positive trend in increasing airspace capacity compared to traditional ATS routes, thanks to its flexible free routing planning which enables more efficient use of airspace. However, when evaluating airspace capacity, it is crucial to consider more than just the number of aircraft present. As described in section Section 2.3, capacity is influenced by various factors, including traffic complexity. The implementation of FRA can introduce a certain level of complexity to the airspace and add complexity to the workload of air traffic controllers.

For example, due to the larger operational area, the workload for the air traffic controllers may increase. Additionally, the potential for conflict detection and resolution may be heightened since the intersection of two or more flights paths are in ”invisible points”. So, in order to assess these challenges and to find the best airspace optimization, existing literature conducts research in creating complexity metrics. These metrics depend on both structural and flow characteristics of airspace. While the structural characteristics are fixed for a sector and depends on the spatial and physical attributes of the sector, the flow characteristics vary as a function of time and depend on the air traffic situation.

In the field of research, one of the commonly used complexity metrics is dynamic density, which combines static and dynamic data. The COCA project, which analyzes the dynamics of the MUAC sector, demonstrates that changes in sector configuration, rather than operational mode, can decrease the level of complexity. Another complexity metric proposed in the literature is the Solution Space Diagram. This metric identifies conflict-free areas and provides guidance for aircraft to avoid potential conflict spaces. A study mentioned in section Section 4.4 concludes that, despite model limitations, this approach proves to be a valuable metric for assessing complexity within a sector. With the implementation of Free Route Airspace a new metric was developed to analyze and distinguish between FRA and ATS routing operational modes. According to a study, based on the geometrical complexity of traffic patterns, transitioning to free flight operations leads to a reduction in the expected number of conflicts. However, it is important to note that FRA presents challenges in identifying conflict situations and determining appropriate resolutions due to the reduced options available to air traffic controllers. There are some research papers which do not explicitly establish a cause-effect relationship between complexity and workload. Instead, they present different approaches for monitoring complexity within sectors, known as Intrinsic Complexity Metrics, which are independent of controller workload. These studies demonstrate that the implementation of FRA can both increase and decrease complexity within a sector.

Thus, the second analysis conducted in this report focuses on the implementation performance of Free Route Airspace in relation to the environment. In light of this, the second research question can be formulated as follows:

How does the implementation of Free Route Airspace, FRA, contribute to the sustainability of air transport?

As discussed in section Section 3.3, the implementation of Free Route Airspace plays a positive role in enhancing the sustainability of air transportation. While the FRA implementation process is still ongoing, the initial results indicate a visible reduction in environmental impact. The FRA concept has been shown to lead to a reduction in fuel burn of up to 2.1%. However, it remains unclear whether this concept has a beneficial impact at a global level, and it is worth noting that accommodating a larger volume of traffic through FRA may result in increased overall emissions. Despite the visible benefits of FRA in terms of environmental sustainability and maximizing sector capacity, there is an ongoing debate regarding the level of complexity it introduces at a network level. The implementation of FRA has implications for airspace management and air traffic flow, and it is important to carefully analyze how these changes may impact network-wide complexity.

In conclusion, the present literature review provides theoretical insights into the main research questions, highlighting the concept of Free Route Airspace as a promising solution for enhancing airspace capacity. However, it is important to acknowledge that the implementation of FRA in Europe is still ongoing, and the studies reviewed have been conducted using existing aviation technologies, which may result in less precise results. While FRA shows potential for accommodating future air traffic growth, it is crucial to conduct a detailed analysis of its impact on traffic complexity. This literature review establishes the foundation for the second part of the master’s thesis project, as outlined in section Chapter 6.

6
Research project

An extensive literature review was conducted to explore the existing knowledge and theories surrounding the enhancement of capacity with respect to the impact of Free Route Airspace implementation on air traffic complexity. The literature study provided valuable insights. Building upon this foundation, the next phase of the thesis aims to compute the practical phase of the research project. Therefore, this chapter describes briefly the future research project. The main steps and variables that will be used in the model are explained in this section of the report.

In order to conduct a research project, it is important to follow a series of steps to ensure a systematic and organized approach. The flow chart of the study is displayed inFigure 6.1. The first step in the research process the problem identification. This involves recognizing and defining the specific problem or research gap that the study aims to address. The introduction section of the research provides an overview of the problem, highlighting its significance and the reasons for conducting the research. During the problem statement phase, the research objectives and research questions are formulated, providing a clear focus for the study. Literature review represents an in-depth analysis of existing literature and research related to the problem. It identifies the current state of knowledge, and sets the foundation for the research by providing the necessary context for the study. These two steps are performed in this report. The findings and conclusions are presented in Chapter 5.

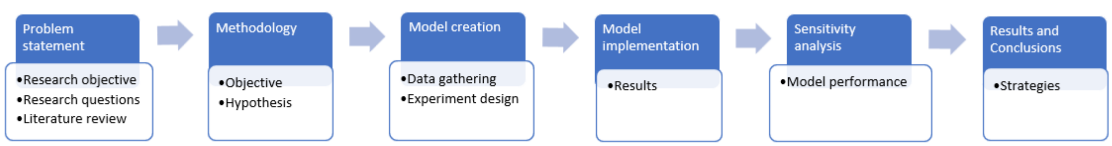


Figure 6.1: Flow chart of research project process

Once the problem has been identified, methodology needs to be described. This phase outlines the overall approach and methods that will be performed to achieve the research objective. Once the methodology is defined, the next phase is the model creation. This step consists of two key components, namely data collection and experiment design. Data collection involves gathering the necessary data or information required to address the research questions and validate the model. In this particular case, the data that will be used in the project will be the exported from EUROCONTROL database. It will taken into consideration the flight trajectories for a 30-days time window. The period that was chosen is the summer month June of 2018. This choice was performed based on the fact that in June represents a high demand month of the year. In other words, children and students begin their summer holiday in this period of time, so the demand in traveling increase. In addition, the experiment will be conducted in a complex en-route environment, namely MUAC airspace. Thus, there will be taken into consideration only the flights within this airspace.

The experiment design phase focuses on designing the specific experiments or simulations that will be conducted using the collected data. On this stage, the definition of the variables that compute the model are defined. There are three independent variables in the model. The first one is characterized by the organizational mode of operations. The simulation of the flights will be computed in two operational environments. Firstly, the aircraft are flying in an ATS route network and secondly the aircraft are within Free Route Airspace. The second independent variable is described by the traffic density. This variable has three conditions: low, normal, and high demand. Finally, the last independent variable that is computed in the model is defined based on the traffic pattern. To explain this variable, three different simulation areas will be performed. Overall, the independent variables are shown in Figure 6.2.

	Low			Normal			High		
ATS routes	Area 1	Area 2	Area3	Area 1	Area 2	Area3	Area 1	Area 2	Area3
FRA	Area 1	Area 2	Area3	Area 1	Area 2	Area3	Area 1	Area 2	Area3

Figure 6.2: Independent variables

In order to complete the model, several dependent variables needs to be considered. As dependent variables, there will be defined three complexity metrics according to Section 4.4. The first dependent variable chosen is the dynamic density. This metric captures the overall behavior of the traffic. This metric will be calculated as it is determined in COCA project. [25] The second complexity metric of interest is the Solution Space Diagram approach. With this metric the conflict rate can be integrated in the model because the SSD is used to monitor the impact of aircraft proximity. Finally, the Fractal Dimension metric represents the third dependent variable. The reason of choosing this complexity metric is that the Fractal Dimension measures the geometrical complexity of a traffic pattern from different operational concepts. So, in this case, the variation of ATS route network and FRA may be emphasized. However, since FRA has a positive impact on environment regarding the reduction of emissions, the fuel efficiency is taking into consideration as a fourth dependent variable.

Once the model is created, it is computed in the experimental software called BlueSky ATM Simulator. This application represents an open-data ATM simulator where can be performed various analyses. The results obtained from the simulations are then analyzed and evaluated. A sensitivity analysis may be performed to assess the robustness of the model and identify the key factors that influence the outcomes. At this stage, an environmental impact model is conducted. Finally, based on the results and analysis, strategies or recommendations can be proposed to address the research problem or achieve the research objectives. These strategies aim to provide practical implications or solutions based on the findings of the study.

6.1. Planning

This section outlines the timeline and planning of the MSc thesis project. Figure 6.3 illustrates the current position on the timeline, which is at M1, corresponding to the completion of the literature review.

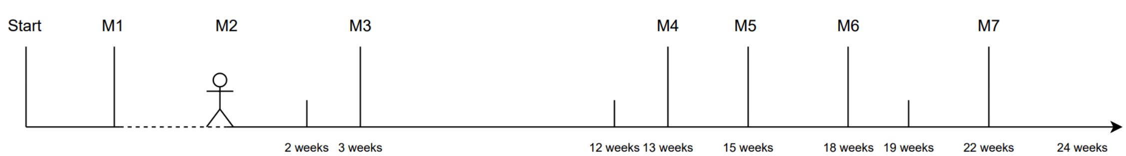


Figure 6.3: Time frame of milestones

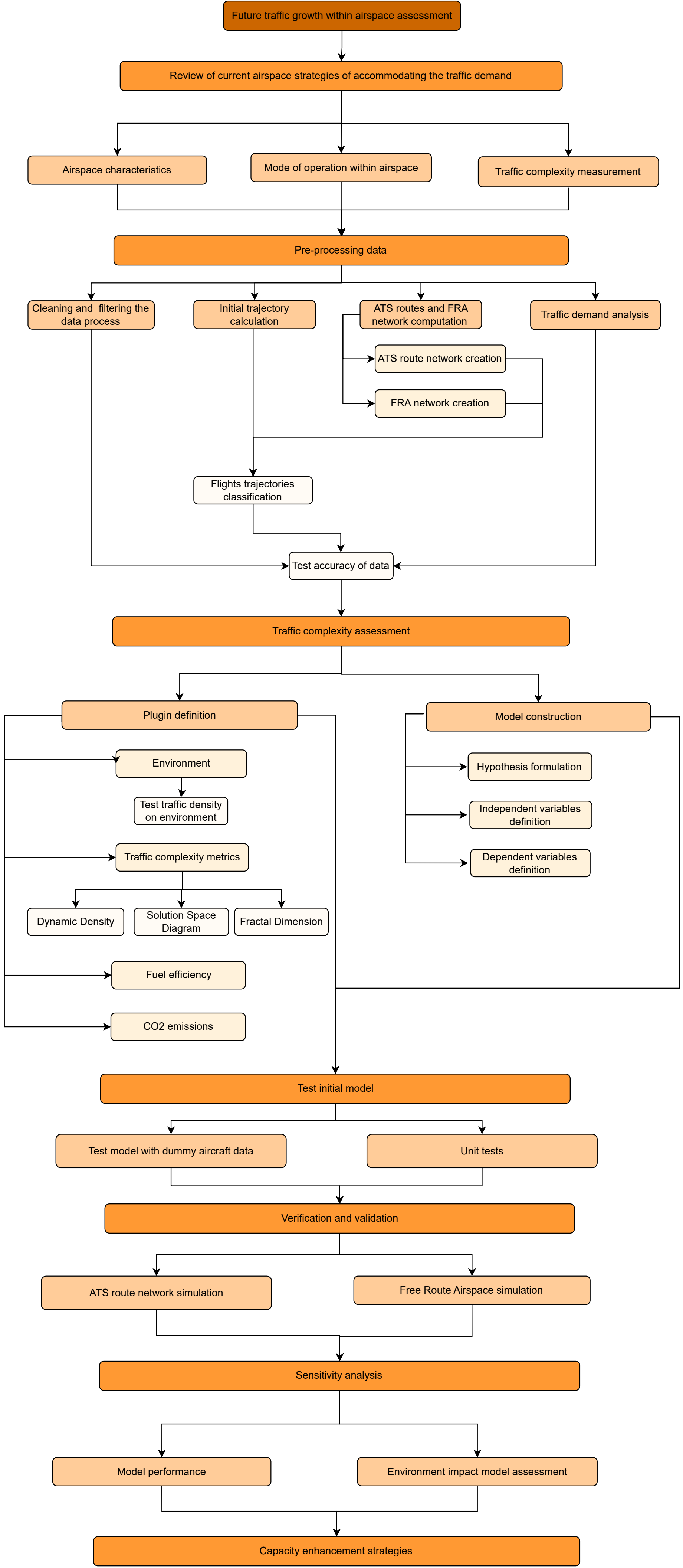
	Milestone		Period
M1	Literature Review		Current position
M2	Pre-processing data	Scenarios creation	2 weeks
		Test	1 week
M3	Traffic complexity assessment	Plugins definition	9 weeks
		Model construction	1 week
M4	Test initial model		2 weeks
M5	Verification and validation		3 weeks
M6	Sensitivity analysis	Model performance	1 week
		Environment impact model	3 weeks
M7	Capacity enhancement strategies		2 weeks
		Total	24 weeks

Figure 6.4: Milestones definition

In Figure 6.4 the milestones of the project are defines as follows. M2 - Pre-processing data. The focus during this phase is to create flight scenarios in the BlueSky software simulator and analyze the sector. M3 - Traffic complexity assessment. In this milestone, different plugins are developed and utilized to assess traffic complexity. M4 - Test initial model. This phase involves conducting unit tests and tests using dummy variables to ensure the accuracy and correctness of the initial model. These tests serve to validate the model's functionality and identify any potential issues or areas for improvement.

M5 - Simulation runs. Here, simulations are executed in the BlueSky simulator for both Free Route Airspace and traditional ATS routes. M6 - Sensivity analysis. During this milestone, key performance indicators, KPIs, are calculated and evaluated to assess the performance of the model. Additionally, an environmental impact model is developed to analyze and quantify the potential environmental effects of the different operational approaches. M7 - Capacity enhancement strategies. The project concludes with milestone M7, where strategies for enhancing airspace capacity are proposed based on the findings and insights from the preceding milestones. This final step aims to provide recommendations and potential solutions for optimizing airspace capacity while considering the complexities and environmental impacts associated with different operational approaches.

All the milestones discussed in the previous section are evaluated and estimated in the comprehensive flowchart of the research project, which is presented in Figure 6.5. This flowchart provides a detailed overview of the project's progression and the interrelationships between the different stages and milestones. The flowchart serves as a visual representation of the project's structure and guides the researcher through the sequential steps necessary to achieve the desired outcomes.


Future traffic growth within airspace assessment
Review of current airspace strategies of accommodating the traffic demand
Airspace characteristics
Mode of operation within airspace
Traffic complexity measurement
Pre-processing data
Cleaning and filtering the data process
Initial trajectory calculation
ATS routes and FRA network computation
Traffic demand analysis
ATS route network creation
FRA network creation
Flights trajectories classification
Test accuracy of data
Traffic complexity assessment
Plugin definition
Model construction
Environment
Test traffic density on environment
Hypothesis formulation
Independent variables definition
Dependent variables definition
Traffic complexity metrics
Dynamic Density
Solution Space Diagram
Fractal Dimension
Fuel efficiency
CO2 emissions
Test initial model
Test model with dummy aircraft data
Unit tests
Verification and validation
ATS route network simulation
Free Route Airspace simulation
Sensitivity analysis
Model performance
Environment impact model assessment
Capacity enhancement strategies

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