The future of free route in the European airspace: A study quantifying the cost-benefits and safety-cost of its implementation

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The Future of Free Route in the European Airspace: A study quantifying the cost-benefits and safety-cost of its implementation

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ABSTRACT

Free-route airspace permits users to freely plan a route between defined entry and exit waypoints with the possibility of routing via intermediate points. Flights flying in a free-route area remain subject to air traffic control (ATC) for separation provision.

This thesis evaluates the free-route airspace implementation in terms of three different scenarios, one of which represents an extreme future scenario of free-route implementation, considering the complete upper airspace of the European Civil Aviation Conference (ECAC) area as a unique airspace block configured with free route.

This research centres on investigating the benefits for airspace users and on the study of possible increments in complexity for such configurations. In this research, fast time simulations are conducted to determine how much flight time, fuel and distance aircraft can be saved with this free-route configuration.

Meanwhile, this thesis also explains the evolution of conflicts derived from potential separation losses between aircraft in this new environment. Free-route separation losses can emerge at any point of the airspace and can require greater effort to be solved compared to fixed airway configurations, where conflicts usually occur in well-known airway intersections.

The airspace configurations modelled in this study consist of the current airspace structure (fixed airways, DCT, partial free route, etc), referred to as Initial, and the future scenario, named Free Route, where new navigation points are added. This research explores the advantages and difficulties that a large-scale application of the free-route concept can bring to European airspace.

Deriving from this study's results, it could be concluded that airspace users experience great benefits from free-route implementation, including important distance savings that can reach 1,30% of the nominal route in a full European free route.

Regarding complexity, this thesis provides important results for free-route implementation, stating that horizontal complexity and conflicts will be increased by Free Route Airspace, as the airspace trajectories and flows become more random, increasing the crossing interactions. On the other hand, however, the vertical and speed interactions notably decrease, producing a global reduction in complexity.

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Glossary

ACC	Area Control Centre
AIP	Aeronautical Information Publication
AIS	Aeronautical Information Service
ANSP	Air Navigation Service Provider
ARR	Arrival
ARTCC	Air Route Traffic Control Centres
ATC	Air Traffic Control
ATCC	Aviation Control Centre
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
ATS	Air Traffic Services
CDM	Collaborative Decision Making
CNS	Communications, Navigation and Surveillance
CTR	Control Tower Region
DCT	Direct Course To
DEP	Departure
ERNIP	European Route Network Improvement Plan

FAA	Federal Aviation Administration
FAB	Functional Airspace Block
FIR	Flight Information Region
FL	Flight Level
FRA	Free-Route Airspace
FUA	Flexible Use of Airspace
GND	Ground
IFR	Instrument Flight Rules
LoA	Letter of Agreement
NEFRA	Northern European Free-Route Airspace
NMOC	Network Manager Operations Centre
NOP	Network Operations Plan
PBN	Performance-Based Navigation
RAD	Route Availability Document
RTS	Real-Time Simulation
SES	Single European Sky
SESAR	Single European Sky ATM Research
SSR	Secondary Surveillance Radar
SW FAB	Southwest Functional Airspace Block

TMA Terminal Control Area

TRACON Terminal Control Centre Centre de Control de Terminal

UIR Upper Information Region

UNL Unlimited Sense Limit

WAM Wide Area Multilateration

WP Waypoint

1. Introduction

Free-route airspace (FRA) has been defined (Eurocontrol, 2018 b) as follows:

> *'A specific airspace within which users shall freely plan their routes between an entry point and an exit point without reference to the air traffic services (ATS) route network. In this airspace, flights will remain subject to air traffic control'.*

According to this definition, it can be stated that the main goal of FRA is to remove the constraints imposed by the fixed-route structure and, through the optimised use of all the airspace, obtain benefits of capacity, flexibility, flight efficiency and cost savings while maintaining safety standards.

As previously mentioned, in FRA, users can flight their preferred trajectories, directly affecting in-flight efficiency. In contrast, the FRA concept presents a significant difference from conventional point-to-point navigation and RNAV routes in terms of the method for establishing aircraft separations.

The FRA employs a group of entry and exit points for users so airliners can fly preferred trajectories based on these points, resulting in significant distance saving, fuel consumption, flight time, CO2 emissions, and more compared to conventional flights using the route network.

However, FRA trajectories also present random behaviour, producing conflict in any zone of the airspace, allowing hot spots to appear anywhere due to the elimination of airways. As such, assessing the complexity and conflicts of FRA represents the primary focus of this PhD thesis.

1.1. Motivation

Numerous FRA areas operate in Europe today, all of which are placed under structural, time or flow constrains that limit the benefits for airspace users.

A full free-route implementation is planned for completion within the next 10 years, and it appears to comprise a fragmented compendium of FRAs working separately and taking the FAB (Functional Airspace Blocks) as a larger reference.

To our knowledge, the widest area that has been assessed as free-route is the Central European FAB (FABEC) as part of the APACHE project (Prats, et al., 2017) but only for one day traffic on the past.

Nonetheless, research into ATM metrics represents another PhD motivation, and one that has historically been conducted in two main areas: safety and capacity. The potential conflicts and complexity of traffic flows are both highly related. In Europe, the limitation on airspace capacity constitutes a safety measure applied at the strategical level, with capacity largely determined by the controllers' workload according to the 'difficulties to manage the traffic'.

Finally, with the constant increase in air traffic demand, studies of the Single European Sky ATM Research (SESAR) initiatives have shifted towards the latest ATM advances and to the airspace modernisation with directs benefits for the airspace users. In this sense, an important target goal of the SESAR is the increase of airspace cost efficiency, which is a target directly addressed by the free-route concept.

1.2. Research Objectives

This doctoral thesis examines the FRA's characteristics across its implementation in Europe, describing aspects such as distance savings, flight time savings, number of conflicts and complexity indicators resulting from FRA implementation in the en-route aspect.

The study focusses on demonstrating that FRA does not increase the complexity and conflicts faced regarding en-route airspace.

The thesis objectives can be summarised in the following points:

- This study investigates the future full free-route implementation environment in Europe without national borders as structural constraints, exploring aspects such as benefits for airspace users and complexity or difficulties related with this scenario. In this sense, this will provide an important opportunity to advance the understanding and evidence regarding the effects of European airspace fragmentation and their consequences in FRA, describing the future problems arising from full implementation of the concept.
- Another thesis objective consists of studying the performance of the current NEFRA and the Southwest FAB FRA. As pioneer airspaces in FRA, these findings should provide an important contribution to the field of both airspaces and will, by means of comparative analysis, permit describing the improvements resulting from implementing the concept.

- Finally, this PhD thesis aims to contribute to this growing area of research by exploring complexity metrics applied to free route and to provide validation by means of an independent indicator for the number of conflicts, correlating the results.

1.3. Outline of this PhD Thesis

This thesis consists of seven chapters. Chapter 1, Introduction, provides a description of the free-route concept and details the motivation and research objectives of this doctoral thesis.

The main portion of this thesis can be divided into two primary parts, with Part I relating to the state of art and airspace description, containing chapters two and three:

- Chapter 2 describes the fundaments and state of art regarding FRA, as well as the main concepts related to ICAO airspace configuration. An extensive review of literature related to free route and ATM metrics is also provided, focussing primarily on those with more transcendence for this work—namely, flight efficiency, potential conflicts and airspace complexity.
- Chapter 3 explains the basis of the thesis simulations, describing the employed metrics and scenario characteristics, as well as the FRA background of each of the airspaces under study.

Following this, Part II details the simulation results and analysis, structured into chapters as follows:

- Chapter 4 describes the study of NEFRA airspace, presenting the main characteristics of the simulated scenario and results.
- Chapter 5 elaborates on the analysis of the SW FAB area. Following a structure similar to the previous chapter, it presents the main simulation results.
- Chapter 6 explains the EUROFRA scenario and results, contrasting and depicting the findings via several graphics.
- Finally, Chapter 7 summarises the main conclusions and contributions of this thesis.

2. Background and State of the Art

2.1. AMT Concepts and SESAR Modernisation

In 1993, the liberalisation of the European Union aviation market made travel considerably more accessible and affordable, stimulating growth in air services. Since then, Europe air traffic has increased by approximately 54%. However, constraints on Europe's airspace capacity have also resulted in more delays.

In this sense, delays have occurred not only because of a shortage of capacity, but also due to the fact that air traffic control (ATC) in Europe is fragmented and inefficient. Nowadays, the European airspace is structured around national boundaries, and so flights are often unable to take direct routes that would save fuel, reduce costs and be better for the environment (Eurocontrol, 2012).

By 1999, with the economic crisis and increase in fuel costs, and following the severe delays for flights in European airspace, the sector's growth rate was momentary reduced. Comparing the European and American airspaces, both approximately the same size, the number of air navigation service providers (ANSPs) for en route equalled 37 for Europe and only one, the Federal Aviation Administration (FAA), for the United States (European Commission, 2018 b). In addition, the number of daily flights in Europe was half that of the United States (30,000 in Europe and 60,000 flights in USA) while the global costs of both systems remained similar (Eurocontrol, The Single European Sky, 2011).

In addition, a comparison to the US (FAA and Eurocontrol, 2019) also indicates that the US ATM system is able to manage 57% more flights with 24% less staff. A major reason for this disparity is that the number of air traffic control centres (ACCs) in the US equals 20, whereas Europe features 62 ACCs. Figure 2.1 provides a general depiction of the aspects related to this comparison.

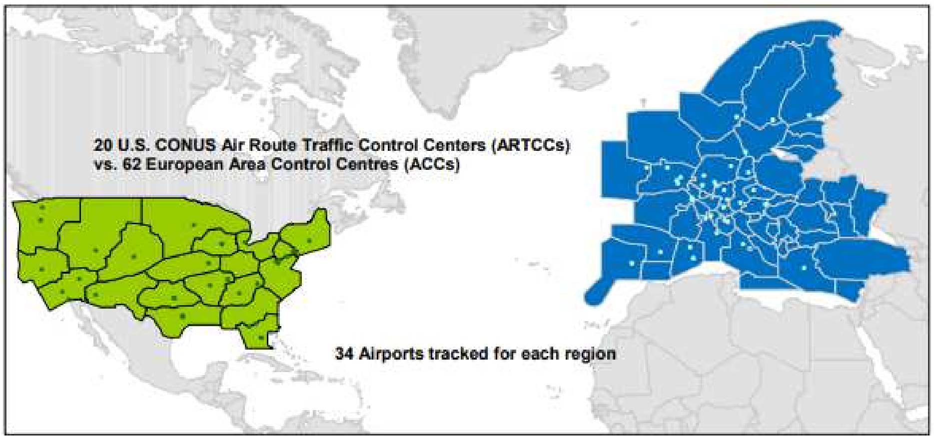

Figure 2.1 Europe and US ATM comparison. Source: (FAA and Eurocontrol, 2019)

In response, in 2000, the European Commission requested Eurocontrol to design a plan for modernising European airspace. In the first deliverable of the SESAR programme, a description of the situation depicted rather safe air traffic, but also fragmented and inefficient management (European Commission, 2000).

As a result, the European Commission, Eurocontrol and the most relevant European airspace stakeholders founded the Single European Sky ATM Research (SESAR) Joint Undertaking. Together, they created and managed the SESAR programme, which funded research and demonstration projects following a performance-driven approach (ICAO, 2008).

SESAR set the basis for the new generation of ATM system to be the assurance of safety and fluidity of air transport in Europe for the next several decades (Skybrary, 2017).

The SESAR programme focusses on modernising European ATC and airspace management with a uniform high level of safety, interoperability and efficiency. SESAR aims to develop a new generation of ATM systems capable of ensuring safety and fluidity of air transport in Europe for the next several decades (Button & Neiva, 2013). SESAR represents the operational and technological element for Single European Sky (SES), which establishes cross-border blocks of airspace.

As part of the SESAR programme, two new operational and technological instruments are being developed to address these challenges: The **FAB** and the **FRA.**

Nowadays, European airspace remains structured around national boundaries, and as such, flights are scarcely able to take direct routes that would save fuel, costs and be more environmentally friendly. The estimated cost of airspace fragmentation in Europe amounts to 4 billion EUR a year (European Commission, 2018 b). These inefficiencies and extra costs largely result from delays for the airlines (€2 billion), route extensions (€1.2 billion) and additional air navigation charges (€0.6 billion) (IATA, 2011).

Today, the SESAR Joint Undertaking (SJU) is leading the implementation and deployment of several FABs in Europe with the goal of improving air navigation service (ANS) performance (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006), but with unequal results (Button & Neiva, 2013). According to the first, 11% of the en-route flight inefficiency is attributable to airway fragmentation between states within each FAB, while an additional 25% is attributable of fragmentation between FABs.

In this sense, and supported by a reduction in airspace fragmentation, it has been mentioned (Steiner, Mihetec, & Rezo, 2019) that, although airspace represents a limited resource, air traffic volume continuously increases across Europe. This has in turn made airspace management more complex and civil-military cooperation more difficult. Thus, to prevent further system dysfunctionalities at the operational level, it is necessary to reduce negative impacts arising from fragmented airspace design.

For all this, one of the key elements of SES is the introduction of FABs. With FABs, routes and airspace structures are no longer defined in accordance with national borders, but rather in accordance with operational traffic needs. The important point from this is that ANSs and related functions are optimised through enhanced cooperation between ANSPs, reducing navigation costs. On the other side, FABs are also expected to increase capacity and flight efficiency for airspace users. According to the future SES programme, the 67 current airspace blocks in Europe (all based on national boundaries) are going to be reorganised into only nine FABs (Eurocontrol, 2018 e).

However, European traffic is continuing to grow at a notable rate. In accord with the network manager forecast (Eurocontrol), the growth rate of IFR movements for 2018 is forecasted to equal +3.3% (±1.3 percentage points (pp)), corresponding to 10.96 million flights, all of which remains in line with the high-growth scenario of the February 2017 forecast.

For 2019, the growth of IFR movements is expected to reach 2.6%, or 11.2 million (±250 thousands). For 2020 onwards, the economic growth remains subject to uncertainties, such as the Brexit negotiations, in this sense, it is expected to experience slowdown, with the continuing increase of average aircraft sizes translating into slightly slower IFR movement growth rates.

Subsequently, after three years of annual growth at or above 3%, European flight growth is expected to progressively slow down to just below 2% per year between 2020 and 2024. In 2024, the forecast is for 12.4 million IFR flight movements in Europe (±1.2 million flights), representing an average annual growth of 2.3% and 17% more IFR movements than in 2017 (Eurocontrol, Flight Movements and Service Units 2018 - 2024, 2018).

The following figure (Figure 2.2) illustrates Eurocontrol's STAFOR forecast from 2018 to 2024:

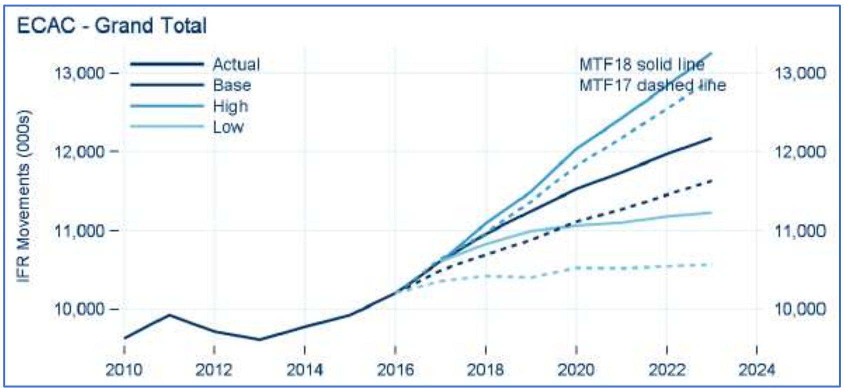

Figure 2.2 Eurocontrol's STATFOR (2018–2024). Source: (Eurocontrol, Flight Movements and Service Units 2018 - 2024, 2018)

With all this, SESAR has to challenge both safety and capacity for the en-route sectors. Implementing these two new operational concepts—the FRA and FAB—can be considered relevant intermediate steps by the SESAR programme to achieve an efficient European airspace by facilitating the implementation of business trajectories and fuel-efficient 4D profiles.

However, determining FAB improvements has presented a challenge for the ATM research community, as this requires an approach from different viewpoints for quantifying benefits for stakeholders (commercial airlines, ANSP, industry, national authority's military, staff associations, etc.). In this sense, to face the challenges of increasing air traffic demand, ANSPs are enhancing en-route air traffic efficiency, such as through introducing more flexible airspace structures and user-driven routes (European Commission, 2018 b), (Eurocontrol, 2011).

2.2. Single European Sky Regulation

The European Commission launched the SES initiative more than 15 years ago, it was laid down in (European Commission, Regulation (EC) No 549/2004) where the framework for the SES creation was placed. The overall objective of SES is to reduce the fragmentation of ANSP in Europe and improve ATM system performance.

It can be said that the SES comprises an initiative oriented to remove boundaries in the air as they were removed on the ground for the single market.

The primary SES goal is to improve the architecture of European ATC, to meet future capacity and safety needs (European Commission, 2018 b).

By improving the overall performance of air traffic management (ATM) and ANSP in Europe, the SES initiative seeks to accomplish the following:

- ➔ Increase airspace **capacity** by three times, as well as reduce delays.
- ➔ Improve **safety** performance by a factor of 10; thus, the total number of ATM-related safety incidents will not increase despite traffic growth.
- ➔ Reduce **environmental** impact by 10%.
- ➔ Reduce the ATM services' **cost** to airspace users by 50%.

The SES structure is based on two packages: SES-I (2004) and SES-II (2009). In addition, numerous supplementary regulations are included (described in Table 1).

2.2.1. SES-I

The first SES package—named SES-I—primarily focussed on airspace capacity. It was launched in 2004, with the first regulation (European Commission, Regulation (EC) No 549/2004) formally establishing the SES:

'The aim of this Regulation is to establish a harmonised regulatory framework for the creation of the single European sky by 31 December 2004'.

One of the main achievements of SES-I is the separation of regulation from service provision through the creation of national supervisory authorities (NSAs), as well as the certification and designation of ANSPs. In the end, this separation provided greater transparency.

Table 2.1 SES-I regulation

Regulation	Base
(European Commission, Regulation (EC) No 549/2004)	Laying down the framework for creating the SES (the framework regulation).

(European Commission, Regulation (EC) No 550/2004)	On the provision of ANSPs in the single European sky (the service provision Regulation).
(European Commission, Regulation (EC) No 551/2004)	On the organisation and use of the airspace in the single European sky (the airspace Regulation).
(European Commission, Regulation (EC) No 552/2004)	On the interoperability of the European ATM network (the interoperability Regulation).

Despite some success, the first package did not generate the level of change required to substantially improve ATM performance in Europe (see Table 2.1). For this reason, a new legislation package was devised to reach the goals initially proposed.

2.2.2. SES-II

To further improve performance, the European Commission proposed a second package of legislation, named SES-II, which was launched in 2009. The main objective of SES-II concerned performance improvement, and it was intended to accelerate realisation of the SES and its benefits with high-level goals to be achieved by 2020 relative to SES-I.

The second regulatory package changed the focus of the SES from capacity to general performance. Its ultimate objective was to increase the economic, financial and environmental performance of the ANSP provisions in Europe. In particular, the amendments to the SES-I regulatory package introduced a comprehensive EU-wide performance scheme, such as refocussing the FABs to concern not just airspace, but service provision in general, and introducing a network manager to co-ordinate certain actions at the network level.

Furthermore, it extended the competences of the European Aviation Safety Agency (EASA) to ATM, and thus shifted rulemaking support for technical implementing rules, as well as oversight of member states, from Eurocontrol to EASA (European Comission, 2018 d).

To achieve these goals, European parliament established a framework of five pillars based on technology, safety, performance, airports and human factors (IATA, 2011). Each of the pillars possessed an independent approximation of performance improvement:

1. **Regulating performance**: Essentially, this pillar covered the establishment of an independent performance review body (PRB) to oversee system performance and set targets. This made FABs mandatory by December 2012 at the latest. It also foresaw the designation of a European network manager.
2. **Safety**: Safety regulation needed to be harmonised and uniformly applied, and so EASA competence was extended to cover aerodromes, ATM and ANSPs. The industry has long supported extending the EASA to be the sole safety regulator for air transport at the European level. With the latest extension of EASA competence, this is now becoming a reality.

   To date, the SES-I and -II packages have focussed on making progress in areas of safety and have further clarified the respective roles of regulators, supervision authorities and service providers. The EASA's evolution to cover ATM and airports also represents an important step towards the supervision of safety across the entire air transport supply chain.
3. **Technology**: SESAR comprises the technological arm of the SES. The aim of SESAR is to provide technical solutions to enable achieving the SES objectives. The current phase is managed by the SESAR Joint Undertaking—a public-private partnership (PPP) comprising the EC and Eurocontrol as founding members, as well as additional members representing airport operators, ground and airborne industry, and ANSPs. Airspace users, the military and professional staff bodies are involved through separate contracts.

   From 2014 onwards, the deployment phase is concerned with the actual implementation of the SESAR solutions.
4. **Airport capacity**: The European Commission is keen to see airports' capacity potential maximised, and has accordingly established an airport observatory for exchanging monitoring information on airport capacity.
5. The package is now recognised as including a fifth pillar on **human factors**, recognising that ATM is and will remain a human-centric activity.

Figure 2.3 summarises the five SES-II pillars described in this subchapter.

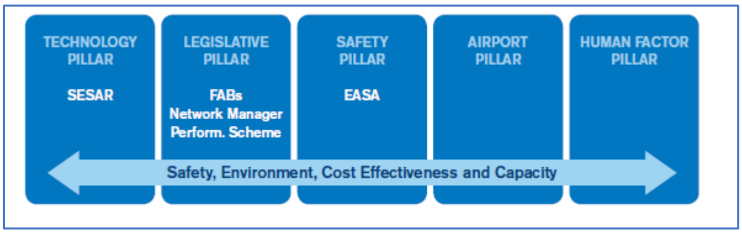

Figure 2.3 Five pillars from SES-II. Source: (IATA, 2011)

As demonstrated in the previous figure, and specifically in the technological branch, the SESAR programme has become a strong focus for numerous stakeholders across the industry.

In this sense, the encouraging results of this development phase have demonstrated that new concepts are feasible; however, the benefits will be considerably delayed and arrive at a reduced level compared to what was originally planned. Most importantly, though, SESAR deployment will only deliver a portion of the SES high-level goals.

2.2.3. SESAR Regulation

As mentioned previously, SESAR represents the technological pillar of SES. It aims to improve ATM performance by modernising and harmonising ATM systems through defining, developing, validating and deploying innovative technological and operational ATM solutions. These innovative solutions constitute what is known as the SESAR concept of operations (European Commission, 2018 e).

As the technological pillar of Europe's ambitious SES initiative, SESAR represents the mechanism coordinating and concentrating all European Union research and development (R&D) activities in ATM, pooling together a wealth of experts to develop the new generation of ATM. Today, SESAR unites approximately 3,000 experts in Europe and beyond.

To reach all SESAR goals, the SESAR Joint Undertaking (SJU) was established in 2007 in order to manage this large-scale and truly international public-private partnership.

This concept is defined in the European ATM Master Plan (European Commission and Eurocontrol, 2015) , which also defines the required operational changes as well as a roadmap for their implementation. The components of the concept are developed and validated by SJU.

The validated essential operational changes are deployed through Deployment Manager and supported by dedicated **SESAR** deployment governance and incentive mechanisms. **All three of these processes (definition, development and deployment)** represent components of a virtual lifecycle that actively involves the stakeholders and the commission in different forms of partnerships.

The SESAR regulation framework established by the European Commission is deployed to assure the process that will close the loop of the SESAR lifecycle and allow SESAR to fully deliver its benefits from concept to implementation.

Through this binding framework, the commission aims to ensure that the SESAR programme evolves rapidly and seamlessly to its deployment phase by creating the right conditions for the timely and synchronised deployment of the essential functionalities of the SESAR concept of operations throughout the European ATM Network.

The main regulations related to SESAR are described in Table 2.2.

Table 2.2 SESAR regulation

Regulation	Base
(European Commission, Regulations (EU) No 219/2007)	Establishing a Joint Undertaking to develop the new generation European ATM system (SESAR)
(European Commission, Regulation (EC) No 409/2013)	SESAR deployment framework
(European Commission, Regulation (EC) No 409/2013), (European Commission, Regulation (EC) No 716/2014)	Pilot Common Project

Finally, it is important to mention that SESAR's vision builds on the notion of trajectory-based operations and relies on the provision of ANSPs in support of executing the business trajectory, meaning that aircraft can fly their preferred trajectories without being constrained by airspace configurations.

In this sense, the next two concepts (Functional Airspace Block and Free Route) are deployed in accordance with SES-II and SESAR.

2.2.4. Functional Airspace Block Regulation

The FAB concept was defined in the first SES legislative package (2004) and further developed in the second legislative package (2009). The creation of FABs represents one of the cornerstones of the SES (European Commission, 2018 a).

Currently, FABs prove vital for reducing airspace fragmentation and are necessary to accommodate the steadily growing traffic, as well as to minimise delays by managing the traffic more dynamically. Objectives for enhancing current safety standards and overall efficiency can best be achieved by increasing the scale of operations, regardless of national borders.

The concept also implies civil-military coordination in airspace and ATM, and under European Union legislation, member states are legally obliged to seek and investigate the possibilities for cooperation that would best meet the objectives whilst ensuring that several requirements are met before establishing FABs through agreements between member states; such agreements should also cover the issues of responsibility and liability.

The service provision regulation (European Commission, Regulation (EC) No 550/2004), as amended by the European Commission (European Commission, Regulation (EU) No 1070/2009), foresees in Article 9a that FABs shall respect the following criteria:

- ➔ Be supported by a safety case.
- ➔ Enable optimum use of airspace considering air traffic flows.
- ➔ Ensure consistency with the European route network established in accordance with Article 6 of the Airspace Regulation.
- ➔ Be justified by their overall added value, including optimal use of technical and human resources based on cost-benefit analyses.
- ➔ Ensure fluent and flexible transfer of responsibility for ATC between air traffic service units.
- ➔ Ensure compatibility between the configurations of upper and lower airspace.
- ➔ Comply with conditions stemming from regional agreements concluded within the ICAO.
- ➔ Respect regional agreements in existence on the date of this regulation's entry into force, particularly those involving European third countries.
- ➔ Facilitate consistency with EU-wide performance targets.

Currently, nine FABs have been established (see Table 2.3), all of which have been declared, established and notified to the European Commission:

Table 2.3 European FABs

FUNCTIONAL AIRSPACE BLOCK
UK-Ireland FAB
Danish-Swedish FAB
Baltic FAB (Lithuania, Poland)
BLUE MED FAB (Cyprus, Greece, Italy and Malta)
Danube FAB (Bulgaria, Romania)
FAB CE (Austria, Bosnia & Herzegovina, Croatia, Czech Republic, Hungary, Slovak Republic, Slovenia)
FABEC (Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland)
North European FAB (Estonia, Finland, Latvia, and Norway)
South West FAB (Portugal, Spain)

Under the previously referred-to Article 9a (1) of regulation (EC), No 550/2004, all European state members have implemented FABs by 4 December 2012.

2.2.5. Free-Route Airspace Regulation

The FRA may be deployed both using direct routing airspace and through FRA. In addition, direct routing airspace is defined laterally and vertically with a set of entry and exit conditions where published direct routings are available.

Within this airspace, flights remain subject to ATC. To facilitate early implementation before the target deployment date, free route could be implemented in a limited manner during defined periods.

The European Commission is fully behind FRA. To this end, their 716/2014 regulation (European Commission, Regulation (EC) No 716/2014) **has a deadline of 2022** for

implementing FRA across Europe above Flight Level 305. The network manager (NM) developed an operations concept a decade ago, along with technical specifications, civil-military requirements and guidance for ANSPs.

According to the 716/2014 regulation, free route will be implemented in steps:

'To facilitate early implementation before the target deployment date specified in Point 3.3, free route could be implemented in a limited way during defined periods. Procedures for transitioning between free route and fixed route operations shall be set. Initial implementation of Free Route may be done on a structurally limited basis, for example by restricting the available entry/exit points for certain traffic flows, through the publication of DCTs, which will allow airspace users to flight plan on the basis of those published DCTs. DCT availability may be subject to traffic demand and/or time constraints. The implementation of FRA based on DCTs may allow the removal of the ATS route network. FRA and DCT shall be published in aeronautical publications as described in the European Route Network Improvement Plan of the Network Manager'.

According to Eurocontrol (Eurocontrol, 2018 b), by the end of 2017, 51 ACCs have either fully or partially implemented FRA operations, exceeding the target of 35 ACCs set by the Network Manager Performance plan.

By the end of 2019, most European airspace is expected to have implemented FRA, with all airspace possessing this type of operation by 2021/2022. This progress results from the close cooperation between the network manager, ANSPs, military partners and airspace users.

For international regulations, ICAO published some documents related to FRA implementation and deployment considerations. One of the most complete reports (ICAO, 2017) presents the FRA design procedures with a focus on the main pillars from the FRA concept and requirements for appropriate FRA AIP publication. In addition, it also presents the approved FRA definitions and offers details concerning all other aspects related to proper FRA implementation in the ICAO EUR/NAT Region.

Below, Figure 2.4 Overview of regulation concepts around FRA presents the main stakeholders and concepts from the regulation perspective.

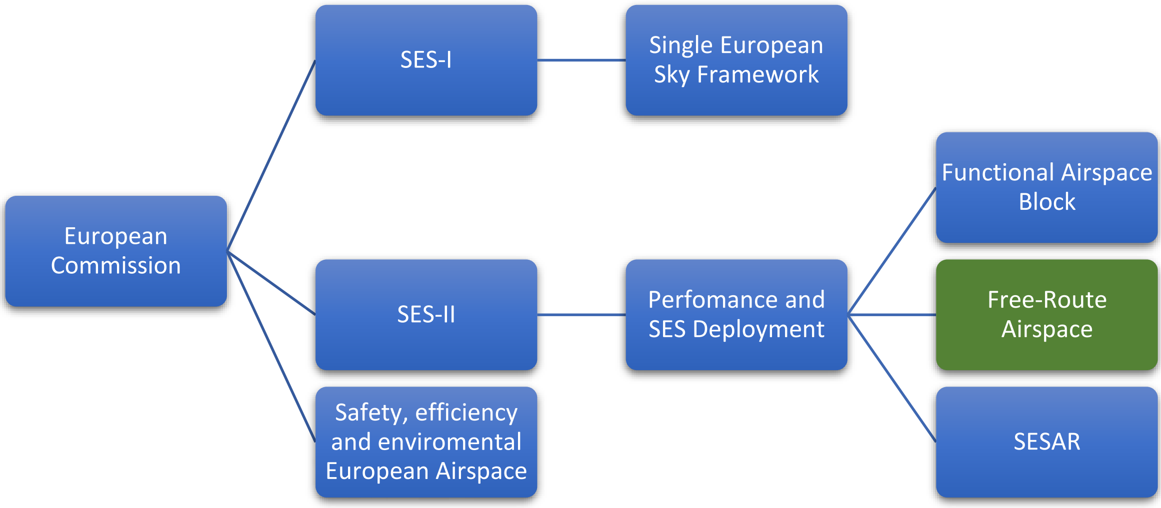

Figure 2.4 Overview of regulation concepts around FRA

According to Figure 2.4, FRA is deployed from the SES framework, and specifically from the second package. In terms of the new concepts FAB and FRA, all regulations are defined by the European Commission.

2.3. Airspace Configuration

2.3.1. European Civil Aviation Conference (ECAC)

The ECAC was founded in 1955 as an intergovernmental organisation with the goal of harmonising civil aviation policies and practices amongst its member states while simultaneously promoting understanding on policy matters between its member states and other parts of the world (European Civil Aviation Conference, 2014).

One of ECAC's missions concerns promoting the continued development of a safe, efficient and sustainable European air transport system.

Nowadays, the ECAC covers the widest grouping of member states of any European organisation dealing with civil aviation. Currently, it is composed of 44 member states, as presented in the map below (Figure 2.5).

Figure 2.5 ECAC airspace cover area. Source: (European Civil Aviation Conference, 2014)

The ECAC's long-established expertise in aviation matters, pan-European membership and close liaison with the International Civil Aviation Organisation (ICAO) enables it to serve as a unique European forum for discussion of every major civil aviation topic.

It also enjoys active co-operation with its sister organisations through Memoranda of Understanding and with the European Commission, Eurocontrol, the European Aviation Security Training Institute and the JAA Training Office.

This PhD thesis works with the airspace configuration implemented in the ECAC area, as well as the FRA concept originated by ECAC state members.

2.3.2. Airspace Classification

In general, two kinds of airspace exist:

- Controlled airspace involves defined dimensions within which ATC service is provided to instrument flight rule (IFR) and visual flight rule (VFR) flights in accordance with the airspace classification.
- Uncontrolled airspace is airspace in which ATC does not exert any executive authority, although it may act in an advisory manner.

The commercial air transport operates in controlled airspace under ICAO flight rules and classification.

According to (ICAO, Annex 11 Air Traffic Services, 2001), the ATS airspace described in 2.3.6 is classified and designated in accordance with the following:

Class A. Only IFR flights are permitted. All flights are provided with ATC service and are separated from each other.

Class B. IFR and VFR flights are permitted. All flights are provided with ATC service and are separated from each other.

Class C. IFR and VFR flights are permitted. All flights are provided with ATC service and IFR flights are separated from other IFR flights and from VFR flights. VFR flights are separated from IFR flights and receive traffic information in respect of other VFR flights.

Class D. IFR and VFR flights are permitted and all flights are provided with air traffic control service. IFR flights are separated from other IFR flights and receive traffic information in respect of VFR flights. VFR flights receive traffic information in respect of all other flights.

Class E. IFR and VFR flights are permitted. IFR flights are provided with ATC service and are separated from other IFR flights. All flights receive traffic information as far as is practical. Class E shall not be used for control zones.

Class F. IFR and VFR flights are permitted. All participating IFR flights receive an air traffic advisory service, and all flights receive flight information service if requested.

Class G. IFR and VFR flights are permitted but only receive flight information service if requested, and no separation or traffic advisory services.

Figure 2.6 provides a summary of the aforementioned airspace classification. Here, it is important to identify the implementation of FRA and FAB concepts and the airspace class A, which constitutes the main airspace of analysis for this thesis.

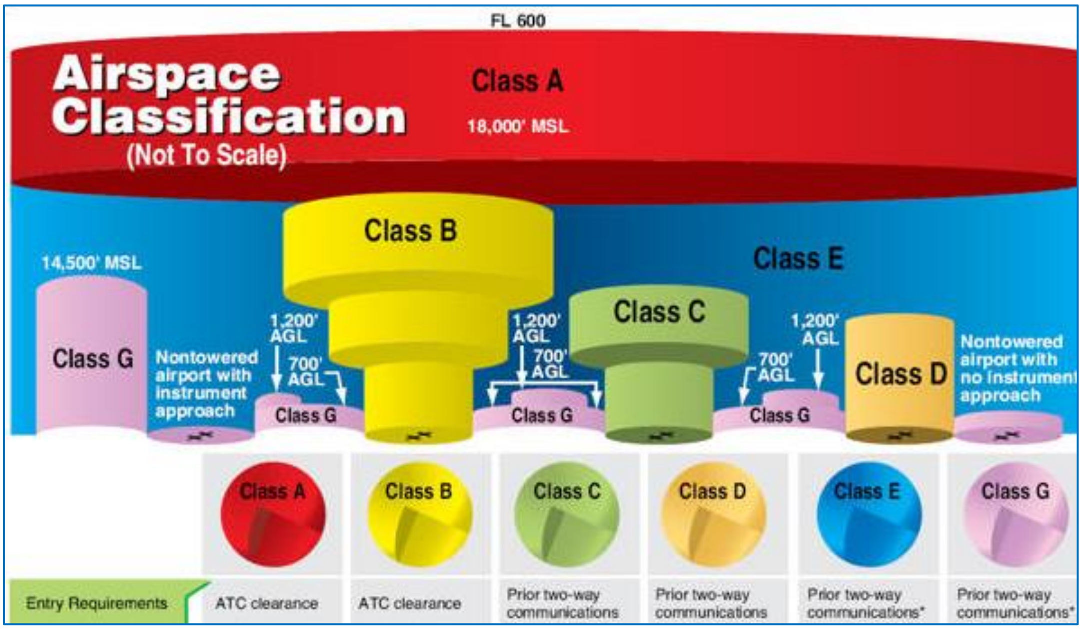

Figure 2.6 ICAO airspace classification. Source: (Krug, s.f.)

The next points define two tactical airspace separations that are commonly defined by ANSPs for managing traffic in a safe and efficient manner.

2.3.3. Flight Information Region

A flight information region (FIR) is an airspace of defined dimensions within which flight information and alerting services are provided:

1. The flight information service is provided for the sake of providing advice and information useful for safely and efficiently conducting flights.
2. The alerting service notifies appropriate organisations regarding aircraft in need of search and rescue aid and assists such organisations as required.
3. There is no standard size for FIRs; it is a matter of administrative convenience for the countries concerned:
    - One FIR for one medium country's airspace.
    - Several FIRs for one large country's airspace.
    - One FIR for several small countries' airspace

Some cases include a vertical division of the FIR, in which case the lower portion remains named FIR, whereas the airspace above is named the upper information region (UIR).

Information and alerting services represent the basic levels of air traffic service, providing information pertinent to safely and efficiently conducting flights and alerting the relevant authorities should an aircraft be in distress (IVAO, s.f.).

2.3.4. Area Control Centre

A FIR is divided into multiple airspaces, termed the area control centre (ACC), with the ACC further divided into a terminal manoeuvring area (TMA), which describes a controlled airspace extending from a lower level to a specified upper level, both at high altitude.

Basically, an ACC represents the airspace in which en-route control service is provided to IFR flights at high altitudes between airport approaches and departures.

Currently, 62 ACCs are active in European airspace (IVAO, s.f.).

2.3.5. Sectors

At the tactical level, airspace is divided into sectors by means of sectorisation, which describes the process of defining sectors across virtual divisions of airspace. Thus, providing air traffic services is decomposed across the different sectors into tasks with manageable workloads.

Opening new sectors does not guarantee the arithmetic sum of the elementary sectors' capacities, as the combined capacity involves a complex combination of factors such as traffic flow direction, coordination procedures, in-sector flight times, and more. Therefore, a capacity figure is calculated for every sector configuration.

Over the years, ATC sectorisation principles evolved into a complex set of criteria that fit within global concepts. Today, ATC sector definition represents an important aspect of the broader process of airspace design (Skybrary, 2017).

New concepts have been developed regarding airspace sector configuration, aligned with the idea of national cross-border operations, but based on traffic flows rather than national borders. One such project from Eurocontrol would be the DAC (Dynamic Airspace Configuration). Here, dynamic sectors are tailored to specific traffic flow patterns with the ability to easily adapt to traffic demand changes regardless of national boundaries in a full FRA environment (Pechenik, 2019).

2.3.6. ATS Route

An ATS route describes a specified route designed to channel the flow of traffic as needed to provide air traffic services.

The term 'ATS route' possesses various meanings: airway, advisory route, controlled or uncontrolled route, arrival or departure route, directs (DCT) and so on.

An ATS route is defined by route specifications that include an ATS route designator, the track to or from significant points (waypoints), distance between significant points, reporting requirements, and, as determined by the appropriate ATS authority, the lowest safe altitude. The ATS route specifications are published in national AIPs (IVAO, s.f.).

2.3.7. Airway

Another important definition concerns the airway, or flight path, which describes a designated route in the air. Usually, airways involve defined segments within a specific altitude block and corridor width, and they are established between the following (IVAO, s.f.):

- Points in airspace based on geographic coordinates named fix(es).
- Radio navigational aids (navaids) (such as VORs or NDBs).
- The intersection of specific radials of two navaids.
- The distance from a navaid using an additional navaid named DME.

Figure 2.7 below illustrates a horizontal representation of airways, which can operate in only one direction or bi-directionally. Furthermore, airways can be crossed by others depending on airspace design and complexity.

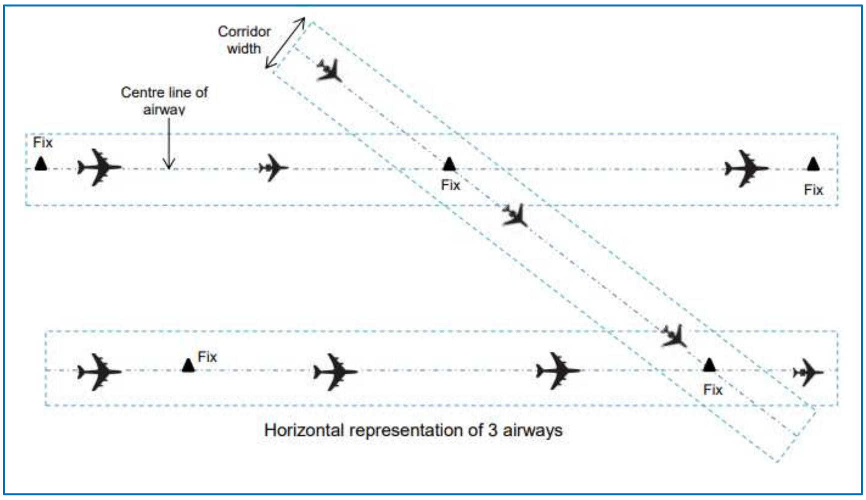

Figure 2.7 Airway representation. Source: (IVAO, s.f.)

2.4. Free-Route Airspace Concept

With the constant increase in air traffic demand, the SESAR initiative is moving towards airspace modernisation with directs benefits for airspace users. An important target goal of SESAR involves increasing airspace cost-efficiency. Consequently, free route is a concept that directly addresses this target.

This concept was first proposed in 2008 by Eurocontrol in cooperation with civil and military experts in airspace design, member states, airspace users, flight-planning organisations and other international stakeholders.

Free route involves eliminating the fixed airways structure, moving from airspace blocks to substituting airways with a set of defined fixes for type—namely, entry, exit, intermediate, arrival or departure (or a combination thereof). In this airspace, users can freely plan a route without reference to the airways network, instead following simple flight rules:

- Flights shall enter the free-route area using an entry or departure fix.
- Flights shall exit the free-route area using an exit or arrival fix.
- Intermediate fixes can be employed to avoid non-flight zones or to follow the flight plan definition rules.

Figure 2.8 presents an example of the free-route area concept extracted from (Skybrary, 2017).

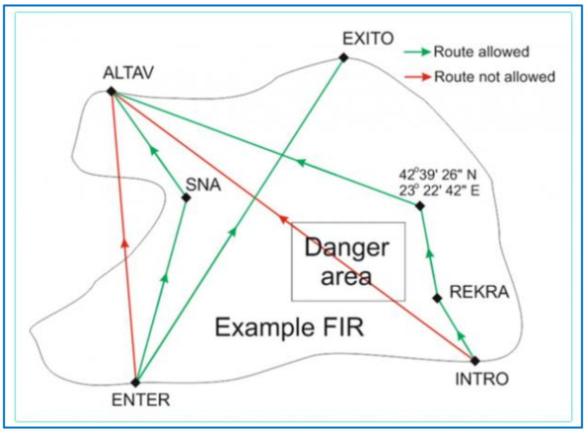

Figure 2.8 FRA concept. Source: (Skybrary, 2017)

As Figure 2.8 demonstrates, free route enables using intermediate waypoints to fly through the airspace, but it is not allowed to plan a free-route flight using external and internal waypoints at that same time or through a forbidden area, even if it is inside the FRA.

In parallel, FRA defines airspace areas where the airspace user can decide on the best performance routes without being subjected to airways or mandatory crossing points. The key element of the FRA concept involves its definition (Eurocontrol, 2018 b):

> ***'In this specific airspace, users may freely plan a route between a defined entry point and a defined exit point, with the possibility of routing via intermediate (published or unpublished) way points, without reference to the ATS route network, subject to airspace availability. The flights remain subject to air traffic control'.***

Here, two main points are important and related to this PhD thesis: First, the preferred planning for the use of entry and exit waypoint to a determined airspace block, and second, and more importantly, the ATC control regarding FRA traffic, which links to changes in airspace complexity and ATC workload.

Adapting aircraft operators to the FRA airspace organisation depends solely on them and how they plan routes by following FRA rules. In general, operators are satisfied with adapting to this change, because for them, FRA offers a means to reduce costs. Both instruments—FABs and free route—have been applied to the same areas in many cases.

It is important to note that, with FRA, airspace users are now faced with a freedom of choice that has not existed during the past 50 years of airspace design and operation. The move from route to airspace availability is offering significant opportunities, and airspace users are gradually adapting their flight-planning systems to fully exploit this concept's full potential. However, it remains their decision as to whether they change their operation and realise the benefits now being offered.

The overall benefits of free-route operations include savings of flight distance by allowing more direct routes. In turn, these flight-distance savings also generate savings in flight time, fuel consumption and jet engine emissions, benefitting both end users and the environment (Nava-Gaxiola & Barrado, 2016) and (Nava-Gaxiola, C.; Barrado, C.; Royo, P., 2018).

These benefits are important for society, but particularly relevant for airspace users, reaching a cost reduction of up to 3.8% if applied to full Europe (Bentrup and Hoffmann, 2016). In (Nava-Gaxiola & Barrado, 2016). A specific FRA partial deployment would enable save around 25,000 NM flight distance per day (between 2 and 3.5% of flight distance).

Another study evaluating direct routes in Europe (Pappie, 2018) identified approximately 95% flight efficiency, indicating that room remains for improvement and for applying more direct routes, such as FRA.

From the airlines side, a specific study (Mas-Mascolo & Riera, 2018) investigated the economic savings linked to an airline—in this case, Vueling—due to implementing FRA. The study determined that, even though FRA is not yet totally implemented, and Vueling does not make excessive use of it, the savings are quite high, reaching an order of 400.000 €. These savings derive from FRA utilisation of approximately 7% of the daily route distance.

Although free-route implementation does not necessarily result in the most direct and optimum route, it does facilitate a closer approach, and compared to a structured airspace, the number of re-routings is lower. The next figure graphically illustrates the flight efficiency gain from a structured airspace to a full free-route capability.

However, the benefits of free route possess several limitations due to the actual implementation, as presented in the following figure (Henn, A., 2015). Structural limitations found in free route's current implementation in Europe, such as national borders or opening schemes, limit these benefits (see Figure 2.9).

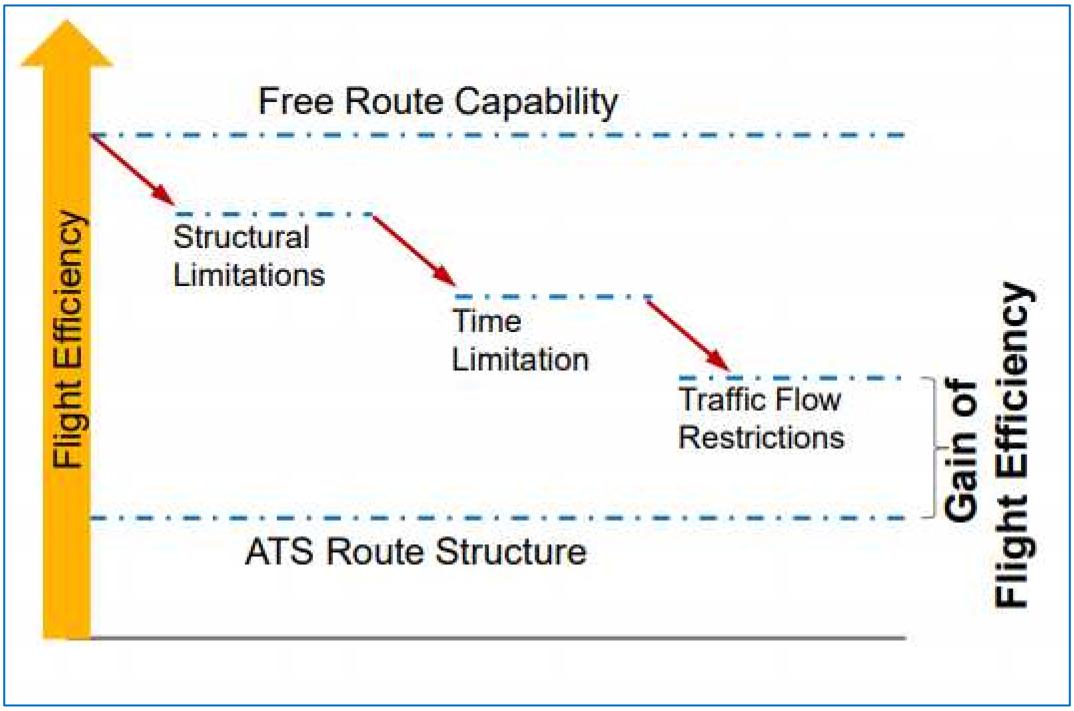

Figure 2.9 Free-route capability. Source: (Henn, A., 2015)

From Figure 2.9, it can be observed that some of the free-route limitations can be solved by new airspace configurations, such as cross-border operations or unifying airspace blocks.

The larger the FRA blocks are, the more gains in flight efficiency can be appreciated by airspace users. In this sense, one of the applications that this thesis evaluates concerns the large-scale application of free route for achieving gains in flight efficiency.

Another study evaluated the free-route concept outside European airspace (Aneeka & Zhong, 2016) and highlighted the estimated amount of key air pollutants, such as NOx and CO2 emitted in the Association of Southeast Asian Nations (ASEAN) region due to current air traffic demand and the potential benefits of FRA implementation in the region.

Furthermore, free route implementation has been studied (Xie, Aneeka, Lee, & Zhong, 2017) at the research level for the Philippines' airspace in applying the FRA structure to accommodate more aircraft under Manila FIR.

Supporting that concept that eliminating free-route constraints will generate better results, in another study (Bucuroiu, 2017), the head of network strategy and development at Eurocontrol indicated that structural sectorisation has to be careful designed, and always according to the need of possessing a cross-border FRA, further mentioning the need for proper sectorisation based on operational requirements without considering how many centres it possesses as long as they are organised properly.

The number of centres is only relevant from an economic point of view. These represent legitimate borders from a political point of view, but from an ATC perspective, they are false borders.

According to Eurocontrol, by the end of 2017, 51 ACCs have either fully or partially implemented FRA operations, exceeding the target of 35 ACCs set by the Network Manager Performance plan. In addition, by 2019/2020, additional savings of between 60,000 and 75,000 NM a day can be expected, along with subsequent fuel, environment and cost benefits (Eurocontrol, 2018 b).

The current FRA projects deployed in Europe are primarily focussed in low-density areas and time periods. One of the special free-route areas possessing high-density air traffic is the Maastricht Upper Area Control Centre (MUAC) (Eurocontrol, 2018 d), (De Herdt, 2018). It has been in operation since 2017 and offers more than 100 direct routes in the upper airspace, all for flight levels above FL245 and available between 23:00 and 05:00. By 2020, Maastricht upper airspace is intended to operate with a 24H free-route concept.

FRA is also currently operating in Portugal (Lisbon), Ireland, DSFAB (Denmark and Sweden), Finland, Romania, Bulgaria, Moldova, Spain (FRASAI), Hungary, Ukraine, and Serbia-Croatia.

In addition, **cross-border implementation** has begun and is already applicable or will soon be so in numerous parts of Europe—namely, SAXFRA (Austria/Slovenia), SEENFRA (Romania/Hungary/Bulgaria), SEAFRA (Servia/Croatia), MALTA/ITALY, and NEFRA (Estonia/Latvia/Finland/Sweden/Denmark/Norway).

Figure 2.10 demonstrates free-route implementation across Europe with the scope placed on 2022, at which point FRA is supposed to be operating in almost all European ACCs.

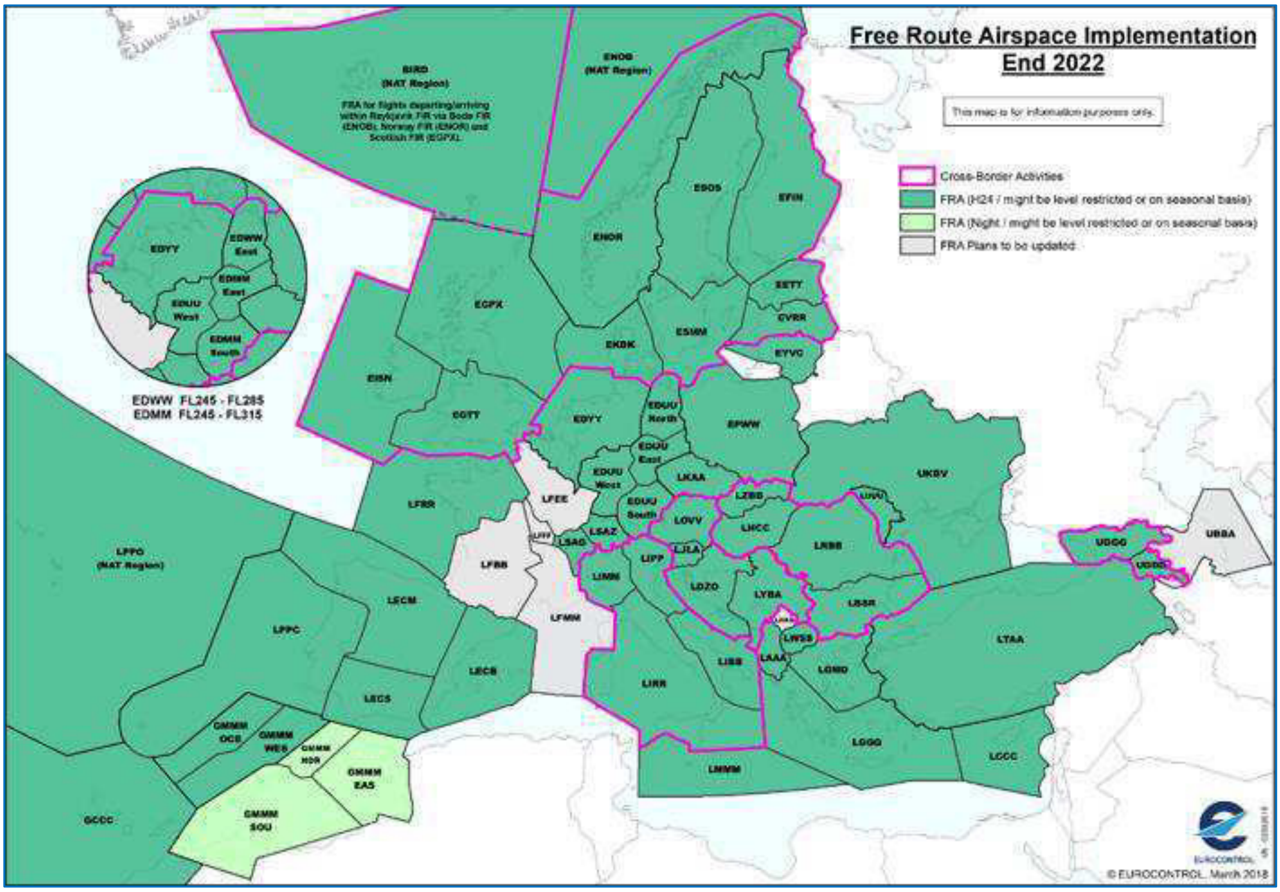

Figure 2.10 European ACC with FRA end 2022. Source: (Eurocontrol, 2018 c)

Regarding airspace flexibility, FRA provides the foundation and flexibility needed to meet the demands of future airspace users over the next 50 years, such as civil and military RPAS, hypersonic transport, spaceplane operations to sub-orbit, wireless network balloons and airships (Eurocontrol, 2018 b).

The benefits of introducing the FRA in the Southwest FAB was measured in another previous work (Nava-Gaxiola & Barrado, 2016). Using the Eurocontrol NEST tool (Eurocontrol, NEST User Manual, Version 1.6, 2018), these benefits were measured for each of the three planned phases of the intended SW FAB (SW FAB Operational Board, 2015). Phase I includes Lisbon and FRASAI airspaces, Phase II incorporates Santa Maria Oceanic airspace, and Phase III concludes with the final integration of the Canary Islands airspace into the Southwest FAB. Results indicated benefits in route efficiency (from 0.73% for phase I to 2.25% for phase III). For Phase III, savings reached up to 32,000 nautical miles per day and approximately 394 tons of fuel. This can in turn save costs approaching 100,000 euros and approximately 100 tons of CO_2 emissions per day.

Another important free-route programme was established on 11 March 2013. Six states of two FABs—Denmark-Sweden (DK/SE FAB) and Norway, Finland, Estonia and Latvia (NEFAB)—signed a declaration of commitment to airspace development. They committed themselves to undertake necessary actions to ensure implementation of the FRA concept above FL 285 in the joined airspace, named.

Today, the **maximum expression of free-route** implementation in Europe was performed by the Northern European countries through an alliance of the ANSPs of nine countries (Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Norway, Sweden and the UK) to build a large FRA project. Basically, the project builds on work initiated through the three existing FAB: the Danish-Swedish FAB, the UK-Ireland FAB and the North European FAB, and both are named **Borealis Alliance.** The nine members of the alliance control more than 10,000 flights a day, reaching over 3.8 million flights a year, or 38% of all flights in Europe (European Comission, 2018 e).

Nowadays, Eurocontrol coordinates the development and implementation of full free-route operations for many ACCs in Europe.

Table 2.4 presents the list of 33 ACCs out of 62 that are currently, either fully or partially, implementing FRA operations in their airspace (Eurocontrol , 2018 a), (Eurocontrol, 2018 c).

Another important characteristic concerns the cross-border free-route implementation, which could vary between full or partial free-route ACC.

Table 2.4 FRA implementation by the ACC (end 2018)

Area Control Centre (ACC)	Free Route Cross-Border	Full Free Route H24	Night/Partial Free Route
Lisbon (LPPC)		▲	
Santa Maria Oceanic (LPPO)		▲	
Shannon (EISN)		▲	
Bodo (ENOB)		▲	
Norway (ENOR)	▲	▲	

Sweden (ESAA)	▲	▲	
Finland (EFIN)	▲	▲	
Tallinn (EETT)	▲	▲	
Riga (EVRR)	▲	▲	
Vilnius (EYVL)		▲	
Koebenvavn (EKDK)	▲	▲	
Tbilisi (UGGG)		▲	
Rhein (EDUU)		▲	
Malta (LMMM)		▲	
Kyiv (UKLV)		▲	
Chisinau (LUUU)		▲	
Yerevan (UDDD)		▲	
Hannover (EDYY)			▲
Rhein West (EDUU)			▲
Rhein South (EDUU)			▲
Kyiv (UKBV, UKDV y UKOV)			▲
Bratislava (LZBB)	▲		▲
Bucarest (LRBB)	▲		▲
Sofia (LBSR)	▲		▲
Budapest (LHCC)	▲	▲	
Wien (LOVV)	▲	▲	
Ljubljana (LJLA)	▲	▲	

Zagreb (LDZO)	▲	▲
Beograd (LYBA)	▲	▲
Milano (LIMM)	▲	▲
Roma (LIRR)	▲	▲

In line with the data described in the last table, and comparing the data presented in Figure 2.10, approximately 50%, that corresponds with 29 European airspaces have not yet implemented free route in any modality. On the other hand, as can be appreciated in the last table, some European FRAs have begun **inter-free-route operations**, which represents one of the points of study of this PhD thesis.

2.5. Functional Airspace Block

Nowadays, the European ATM remains organised in a fragmented way, mostly according to national boundaries. This fragmentation results in capacity limitation and adding to this, it increases cost and can potentially affect safety.

Nevertheless, one of the key elements of the SES involves **introducing cross-border airspaces defined like FABs**. Within the FAB, the routes and airspace structure are no longer defined in accordance with national borders, but rather in accordance with operational traffic needs. The ANSPs and related functions are optimised through enhanced cooperation between ANSPs, reducing navigation costs. On the other hand, FAB are also expected to increase capacity and flight efficiency for airspace users (Eurocontrol, 2018 e).

The origin of FAB concept development across Europe began with MUAC, as the first multinational, cross-border ANSP. MUAC provides ATC for the upper airspace (FL 245+) of Belgium, the Netherlands, Luxembourg and North-West Germany. Consequently, this airspace has proven the FAB concept by showing the advantages of this kind of international cooperation (Eurocontrol, 2016).

Currently, MUAC is integrated as part of the FABEC (Central Europe FAB). According to the SES programme, the current reorganisation of 62 airspace blocks in Europe (all based on national boundaries) are going to be reorganised into only nine FABs.

The first study introducing the FAB concept in the current SES regulation (Wilmer, 2001) referred to FAB as a tool that would replace current upper-controlled airspace operated by ANSP. Today, the regulatory framework where FABs are developed are settled in the first legislative package of the SES-I as one of the primary means for reducing airspace fragmentation. The SES-II tackles the creation of FAB in terms of service provision, in addition to airspace organisation issues. Regarding specific regulations mentioned in section 2.2.4 of this thesis, the FABs were defined (European Commission, Regulation (EU) No 1070/2009) amending (European Commission, Regulation (EC) No 549/2004) as an airspace block based on operational requirements and established regardless of state boundaries, where the provision of ANSPs and related functions is optimised through enhanced cooperation among ANSPs or, when appropriate, an integrated provider, and always in a performance-driven perspective (European Commission, 2018 c).

The nine FABs proposed by the European Commission are depicted in Figure 2.11, and they are further summarised in section 2.2.4. In addition, each FAB and state member can be consulted in Table 2.3 (European FABs) of this document.

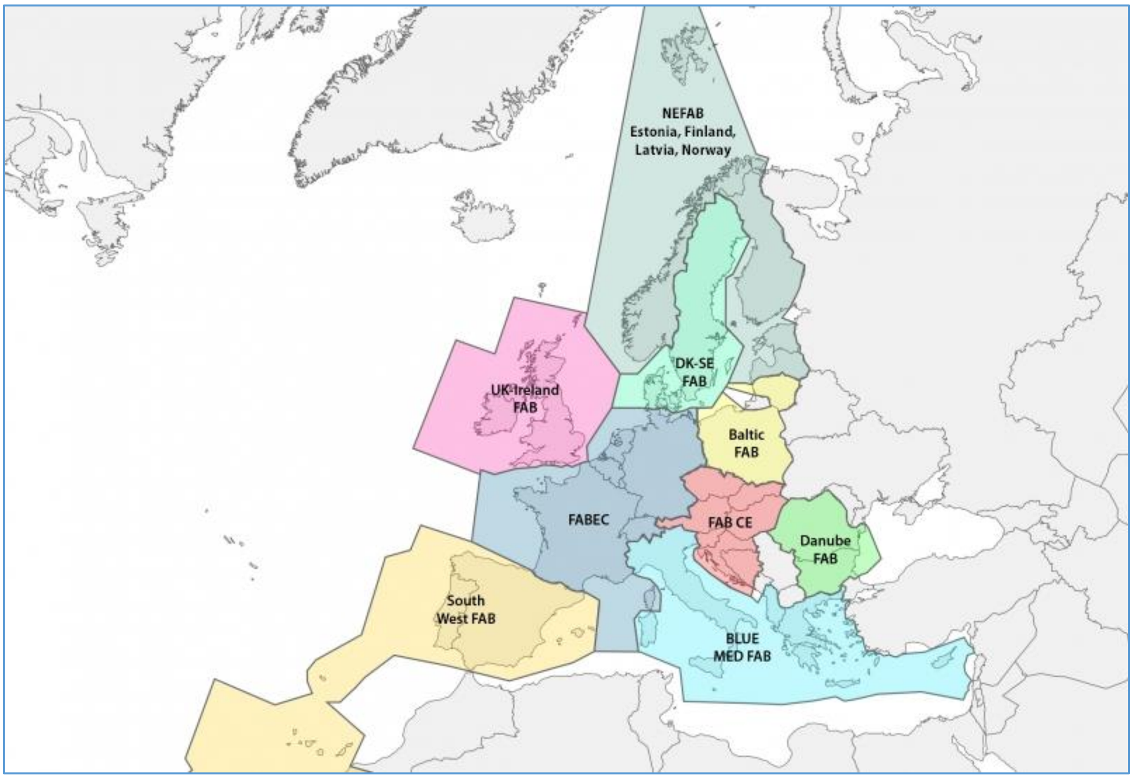

Figure 2.11 Nine European FABs. Source: (Eurocontrol, 2018 e)

As can be seen in Figure 2.11, the oceanic areas are not included in the FAB scope, but those airspaces remain part of the ECAC area. Moreover, the SESAR programme's main goals for FAB implementation (Eurocontrol, 2018 e) are oriented towards the following:

1. Safety: Ensure an improved safety level despite civilian traffic growth.
2. Capacity: Meet the anticipated increase in civil air traffic demand.
3. Cost-effectiveness: Balance the cost of operations within FABs by establishing more effective route structure and ATC service.
4. Flight efficiency: Improve flight efficiency through improvements in routes, flight profiles and distances flown.
5. Environment: Reduce the impact on the environment through improvements in routes, flight profiles and distances flown.
6. Military mission effectiveness: Improve military mission effectiveness through improved training capabilities and readiness postures as required by states.

2.6. Background of Air Traffic Management Metrics

As with many other industries, the airspace 'industry' has decided to employ the performance-based approach (PBA) to face the challenges of increasing air traffic demand. The ICAO Manual on Global Performance of the Air Navigation System (ICAO, 2008) defines PBA as 'a decision-making method based on three principles: strong focus on desired/required results, informed decision making driven by those desired/required results, and reliance on facts and data for decision making'.

Following this approach, in its Master Plan, the SESAR programme identifies the 'need for a single, simplified European ATM System coupled with a performance-based approach that will satisfy all stakeholders' requirements'. Two important items can be extracted from these two documents: First, the need to rely on data to make decisions and follow results, and second, the importance of defining metrics for all involved stakeholders.

In fact, Eurocontrol evaluations mentioned that FAB establishment between state members will need to be supported and justified by its overall added value based on cost-benefit analyses, considering that operational advantages are linked to all stakeholders (Eurocontrol, 2005).

Similar concepts were presented by (Pavlova & Zadorozhnia, 2014), who provided a detailed analysis of the implementation status of FRA and performance-based navigation within the European region, including Ukrainian air navigation systems, concluding that the next step for developing and implementing FRA and PBN in Europe will convey sufficient benefits, such as cost-efficiency, reduced CO2 emissions in the atmosphere, and safety enhancement by establishing additional procedures for flight operations.

Three recent SESAR projects, APACHE, AURORA and INTUIT (Marco, Sánchez, & Prats, 2017) addressed as objectives the proposal of metrics for the ATM. While AURORA focused in metrics useful to airspace users, such as fuel cost or lack of equity, INTUIT applied visual analytics and machine learning to compare route length and time differences. APACHE was very extensive, proposing key performance indicators on the 11 key performance areas defined by SESAR (Mirkovic, et al., 2017).Then the project limited the evaluation to a subset of the 40 proposed indicators.

In (Netjasov, F.; Crnogorac, D., 2017) the details of the 7 safety indicators measured (plus 4 sub-indicators) are calculated for 2 hours of traffic in FABEC. Also values for inefficiencies on fuel and distance, and measures of delays and number of controllers are provided for the same area. For the inefficiency indicators a free-route area is proposed.

Supporting the idea that ANSP first needs to understand the operational capacity and congestion risks associated with a network, and then develop strategies accordingly, Pan and Lishuai (Pan & Lishuai, 2018) identified new opportunities that have arisen from the availability of large-scale aircraft tracking data and many other digitalised records of operations, developing a novel data-driven framework that characterises the operational structure and dynamics of an air traffic network using actual tracking data.

The framework includes several new statistical measures and data analytic techniques to summarise airspace availability, network structure, and utilisation patterns and to apply it to US and Chinese ATM networks in the pursuit of improved flight efficiency.

Another study devised a novel approach to new ATM metrics in (Ruiz, Lopez-Leones, & Ranieri, 2018) involving a novel performance assessment framework and methodology adapted to the TBO (Trajectory-Based Operations) concept. The study proposed assessing performance areas (KPAs) of safety, capacity, and flight efficiency in line with recent ATM trends.

2.6.1. Route Efficiency

The free route approaches an ideal air transportation system where all aircraft could fly their optimal trajectories between airports. In two dimensions, this constitutes the most direct route (not considering wind conditions) from origin to destination. This optimum route will also proportionally reduce time and/or fuel. However, real-world constraints such as route structure lead to aircraft flying less efficient trajectories. Accordingly, Reynolds (Reynolds, 2009) studied the sources of flight inefficiencies and presented several metrics for their measurement.

Although free-route implementation does not necessarily result in the most direct and optimum route, it does facilitate a closer approach. Compared with a structured airspace, for instance, the number of re-routings is lower. Nevertheless, free route's benefits face several limitations due to the actual implementation. Examples include structural limitations, such as national borders, or opening schemes, found in the current implementation of free route in Europe today.

Regarding route efficiency, Zou (Zou, 2013) investigated the airspace user and presented metrics for flight efficiency. The authors defined flight inefficiency in terms of fuel consumption using three alternative approaches: ratio-based, deterministic and stochastic. Ratio-based indices relate a unit of burned fuel with some output metrics such as distance or economic benefits to passengers.

The deterministic frontier model employs a linear function to model fuel consumption. The stochastic frontier model introduces a new term in the previous linear formula to model idiosyncratic errors. The new term is 'stochastic' and follows a half-normal distribution.

Analysis was performed for 15 airlines accounting for 80% of the fuel consumption in US domestic airspace. The resulting ranking of companies' flight inefficiency derived from each of the metrics did not illustrate strong differences, with average fuel inefficiencies of 9–20%.

At the strategical level, Wojcik (Wojcik, 2013) presented metrics measuring the flexibility provided by a departure queue management system based on collaborative decision making (CDM). The authors utilised fast time simulations of aircraft departures and illustrated several delay-related metrics to compare inter-airline exchanges vs. intra-airline exchanges only.

Furthermore, Vaze (Vaze, 2011) evaluated different slot allocation schemes and provided results using delay-related metrics, but also airline operating profits and passenger-related indicators. Strategic planning was proposed to improve cost-efficiency in case of capacity reduction. The delay metric is provided as a ratio of minutes between different studied capacities.

In a similar approach, Lee (Lee, 2011) evaluated the benefits and feasibility of the flexible airspace management concept (FAM) from different perspectives. This concept comprises part of the NextGen implementation plan and allows dynamic reconfiguration of the airspace structure. They modify sector boundaries in order to balance air traffic peak demands over capacity.

The evaluation was performed through simulation and considered the efficiency interests of the airlines (flight distance and time), the controllers' taskload (number of reroutings, aircraft counts) and safety issues (bad weather penetrations, separation violations). Since the simulations feature human-in-the-loop, useful subjective information is also obtained concerning the roles, procedures and tools.

In the case of FRA and flight planning with ATM constrains, another study (Drupka, Majka, Rogalski, & Trela, 2018) focussed on a flight-planning algorithm to introduce the notion of FRA airspace as a mathematical model. In this way, airspace was simulated as a set of squares or cubes possessing volumes with appointed values due to certain conditions in the considered time (i.e. traffic flow or weather).

The studied model ensured facilitation of flight route planning and warranted aircraft separation for the sake of flight safety assurance, assuming that the airspace model will aid airspace users in selecting essential flight plan criteria, such as economy, time, and more. It further concluded that FRA requires implementing a reliable system to properly handle enormous traffic. For this reason, many ANSPs begin by implementing FRA in night-time windows.

2.6.2. Conflicts

An aircraft conflict can be defined as a '**predicted violation of separation of assurance standard**'. In the managed airspace, a conflict occurs when two or more aircrafts occupy the same altitude, within 1000 feet of one another, and come within less than 5 NM (nautical miles) of each other.

The conflict detection process involves predicting trajectories, detecting loss of separation and deciding when actions should be considered (Geser,A.; C. Muñoz, 2002) (Dowek.G, L.C, & Geser.A, 2001). Conflicts are calculated for traffic cruising the EUROFRA and using the separation distances provided above—namely, 5NM in for lateral/longitudinal and 1000 ft for vertical separations (see Figure 2.12**¡Error! No se encuentra el origen de la referencia.**).

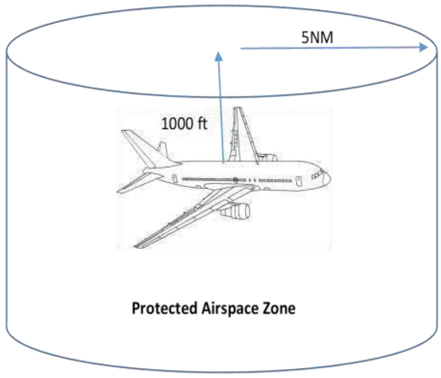

Figure 2.12 Conflict protected airspace zone

The applied indicator involves the number of separation losses averaged for all runs. This reflects an estimation of the number of potential traffic separation infringements.

Considerable previous work has been conducted on conflict prediction and resolution (CDR). Considering the taxonomy proposed by Kuchar and Yang (Kuchar & Yang, 2000), CDR models were categorised according to the following:

- Dimensions of state of information (vertical, horizontal or 3D).
- Method of dynamic state of propagation (nominal, worst case, or probabilistic).
- Management of multiple aircrafts (pairwise or global).
- Conflict detection threshold and others.

A large number of studies have investigated the area of conflict detection (Dowek.G, L.C, & Geser.A, 2001), (Geser,A.; C. Muñoz, 2002), (Yi-Jen, Klosowski, Lee, & Mitchell, 1997), (Kelly III, W.E.;Collins R., 1999), (Alam, Lokan, H, Ellejmi, & Kirby, 2010). Some have modelled aircraft trajectory using 4D vector geometry and determined the closest point of approach between two linear segments and the time remaining until the protection separation standard is violated. If the closest point of approach is less the minimum distance, and the time remaining for separation loss remains within a look-ahead window, then a conflict is declared. Conflict detection methods are embedded in current short-term collision avoidance tools.

Another proposed method for conflict detection is based on ADS-B data, as proposed by Kwangyul and Hyochoong (Kwangyul & Hyochoong, 2012), where developed an efficient and accurate algorithm to calculate conflict probability based on approximating the conflict zone by a set of blocks. This considers the next-generation ATC system ADS-B to broadcast an aircraft's identification, positional data, and operation information to other aircraft nearby in the airspace in question.

These tools can help the ATC anticipate conflicting situations, but they are rarely used to evaluate *a priori* situations due to the lack of predictability at the tactical level.

The process for calculating conflicts may integrate a random uncertainty related to the lack of precision. This involves the probability error of predicting that an aircraft will be in the exact waypoint position at the expected time. This forces the introduction of a standard deviation in trajectories (for instance, some seconds).

Many studies have focussed on the structured airspace, where conflicts are normally found in known merge navigation fixes or in airway crossing points. Air traffic controllers solve potential loss of separations with vectorisations, altitude or speed changes or re-routing to alternate network fixes. In FRA, the separation losses between aircraft can emerge in any point of the airspace.

2.6.3. Metrics to measure human's workload

The ELSA project (Gurtner, 2017) built an agent-based air traffic simulator to evaluate new air traffic operational concepts. Using simple software agents, ELSA simulated mechanistic controllers. The project conducted several runs with close to 2 thousand synthetic trajectories-derived indicators and planned flights from the area of central Italy. Strategic and tactical levels of de-conflicting were examined.

The results were obtained by counting the actions required by the ATC agent. This number was defined as a new complexity indicator and was compared with another 20 metrics from literature. They found that, in free routing, air traffic controllers perform fewer operations, but these actions are dispersed across a large portion of the airspace. This dispersal factor can potentially increase the complexity of the air traffic controllers' work, and thus their workload. Results also indicated the existence of a quadratic relation between this complexity indicator and density. Using regression and principal component analysis techniques, the authors also demonstrated that the four metrics from Chatterji (Chatterji, 2001) directly related to the number of ATC agent actions, in this way validating the ELSA proposal.

For instance, introducing new operational procedures at the tactical level has been assessed by (Knorr, 2011), (Ryerson, 2011), (McNally, 2013), (Gaydos, 2013). The effect of cruise-speed reduction on delay absorption was evaluated by (Knorr, 2011) using metrics of fuel consumption.

The same metrics have been employed to assess three other operational performance measures (schedule aircraft, airborne delay and departure delay) (Ryerson, 2011). Dynamic weather routes provide a promising system that searches and proposes changes in cruise route depending on weather situations (threads, winds, etc.). One study (McNally, 2013) analysed a commercial company's flights during a three-month period, proposing route changes through an automated system. The utilised metrics consisted of flight minutes saved and the impact of rerouting for the sector congestion. Gaydos (Gaydos, 2013) measured the increase in the number of medium-term conflict resolution advisories produced by trajectory-based descents.

2.6.4. Metrics on safety

As previously mentioned, research on air traffic metrics has largely concerned the areas of safety and capacity. The potential conflicts, and the complexity of the traffic flows, directly influence these two areas, and both remain highly related.

In Europe, the limitation in airspace capacity represents a safety measure applied at the strategical level. Capacity is largely determined by the controllers' workload (De Prins,J. and Gómez Ledesma, R., 2008), because, despite upgrades in the onboard systems, humans still constitute the core of the ATM system (Schäfer, Modin, & Scrivani, 2003).

Pozzi (Pozzi, 2011) focussed on evaluating safety as a way to highlight the gap occurring when attempting to transform large amounts of real-time data into operationally relevant recommendations. The authors combined big-data processing systems with operational expertise to detect loss of separation and predict dynamics of disturbance propagation. The safety data processing system was evaluated using real-time radar data at the Italian ANSP (ENAV) experimental centre.

The research focus on the necessity of involve experts to identify patterns after the quantitative big-data processing. The aircraft synchronisation concept (Zanin, 2013) represents another metric proposed to measure airspace safety given a list of aircraft trajectories. This metric accounts for aircraft that possess some degree of dependent behaviour and appear to provide an effective indicator of the loss of separation situations, especially by some previous route deviation action.

In the case of conflicts and the free-route concept, a specific approach regarding FABEC FAB and conflict analysis was presented by (Netjasov, Crnogorac, & Pavlović, 2019), who proposed a set of safety indicators based on potential safety occurrences (conflicts). The developed model contains three modules: the separation violation detection module, the TCAS activation module, and the risk of conflict assessment module. This was tested using planned flight trajectories crossing French and FABEC airspace during 24 h, covering several ATM improvement scenarios like FRA, continuous climb or a combination of both, as well as different traffic-demand levels.

An interesting approach to free-route conflict resolution in a pre-tactical level was devised in the mathematical study by (Ramazan Kursat & Cetek, 2019), who proposed a two-step solution approach for aircraft conflict resolution and fuel consumption due to resolution manoeuvres occurring in free-route airspace. The proposed model sought to provide a mathematical basis for a decision-support system used during the pre-tactical conflict resolution in ATM.

2.6.5. Complexity

Given that the number of conflicts do not completely figure the workload of the air traffic controller, aviation communities have been deeply interested in developing new quantifiable metrics using the term ‘complexity’ (Kopardekar, 2009) (Vogel, 2013). Air traffic complexity aims at providing ‘a measure of the difficulty that a particular traffic situation will present to an air traffic controller’ (Schäfer D. M., 2003), but is implemented with a large number of metrics. For Gurtner (Gurtner, 2017), ‘The number of controller’s actions’ was used to separate the traffic by a simulated ATC agent, while in the study by Flenera (Flenera, 2007), this is determined by the number of flights within a managed sector, near its border, and on non-level segments.

Introducing the human models in the complexity factors has resulted in significant correlation between traffic complexity and workload when evaluated in a fast-time simulation. In contrast, authors have remained unable to identify any significant correlation between workload and the level of safety, even when modelling the effects of temporal delays on human activities. Meanwhile, Timar (Timar, 2013) presented a benefit analysis to assess the performance-based navigation (PBN) applied in standard terminal arrival (STAR) procedures with shared fixes. A queue model was accordingly proposed for the Northern California Metroplex. The results illustrated the traffic distribution, airspace utilisation and throughput (as percent of the capacity) for several routing alternatives and RNAV performances. All these metrics were provided from the perspective of the ANSP, but not for any other stakeholder.

Another study (Toy, 2015) described two types of complexity related to airspace and ATC systems: inherent and apparent. Inherent complexity relates to affecting factors such as weather, terrain, airspace restrictions, traffic density, traffic flows, aircraft performance characteristics, abnormal events, and so on. Inherent complexity is limited to the characteristics of the traffic situation itself, and is thus considered a factor causing workload. Future refinements of the complexity calculation will largely depend on the availability of more accurate data.

For that reason, some new approaches consider 4D trajectories instead of linear vectors. To this end, trajectory-based complexity (TBX) metrics offer a modified aircraft counter. The main advantage of the TBX is that it can be computed easily, and thus communicated in real-time. This fact makes TBX highly appropriate to predict sector complexity under the business trajectory SESAR concept.

The Eurocontrol's working group on complexity defined a new indicator—the complexity score (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006). Two main metrics define the complexity score: adjusted density and structural index. The adjusted density evaluates the potential interactions resulting from density, including uncertainty in trajectories and time, while the structural index balances the density metrics according to interaction geometry and aircraft performance differences. These metrics reflect the difficulty of managing the presence of several aircraft in the same area simultaneously, particularly if those aircraft are in different flight phases and possess different performances and/or headings.

For instance, Yifei (Yifei, 2011) proposed new methods to assess air traffic complexity beyond the traditional taskload metric derived from the rate between traffic demand and capacity. Airway geometry and a complex collision risk model were combined in a non-linear function to obtain coloured maps illustrating the complexity levels at different spots of the airspace.

Idris (Idris, 2013) estimated a sector's capacity from a risk mitigation metric. In this pursuit, adaptability referred to the number of feasible trajectories available to an aircraft that avoid traffic constraints. The arrival traffic of two sectors of the Chicago O'Hare airport were employed for the analysis using two different control strategies in a metering situation: a human path stretch strategy and an alternative automated one. The paper illustrated the relation between adaptability and capacity, but also how automation level influences the controllers' tasks in the estimation. Traffic for the Denver International Airport, estimated at 90 minutes long, involved 80 aircraft, 36 of which were in descent while the rest were en route. An average of one false alarm every 2.5–3 minutes illustrated that the current tools are not acceptable for dealing with trajectory-based descends.

Related to FAB measures, Mihetec et al. (Mihetec, T., et al., 2012) indicated that the number of operational concepts currently in place under FAB implementation makes it difficult to meet the objective of a win-win situation for the individual stakeholders.

Other European studies have focussed on complexity, such as the research by Rezo and Steiner (Rezo & Steiner, 2019), whose research was based on performance review unit (PRU) data and its computation gathered from 37 European ANSPs, similar to that which is proposed in this thesis. According to their results, the existence of differently associating areas within European airspace leads to the conclusion that European airspace is fragmented into different homogeneous and sized spatial patterns identified within the described research paper. However, it does not describe how complexity regarding free-route implementation is affecting the airspace blocks.

From another perspective, qualitative research on ATC complexity and free route has also been conducted (Nava-Gaxiola, C.; Barrado, C., 2016) (Antulov-Fantolin, Rogosic, Juricic, Billiana, & Andrasi, 2018). For instance, (Antulov-Fantolin, Rogosic, Juricic, Billiana, & Andrasi, 2018) conducted an evaluation to determine how FRA influences air traffic controllers, concluding that, with the implementation of specific FRA (SEAFRA), traffic complexity is increased and controllers experience difficulty in detecting conflict in advance, since there are no more old 'hotspots' to concentrate on. Hence, the entire airspace is considered a hotspot.

These conclusions were based on opinions from 34 ATCOs from Zagreb ACC that are actively working on FRA, concluding that traffic complexity, situational awareness and conflict detection has increased, as has the workload for those categories. However, despite an increase in conflict detection, ATCOs also stated they faced no problem whatsoever in conflict resolution. In fact, precisely 50% of them stated that conflict resolution is at a moderate level. In addition, they reported that they can handle the same or even more traffic than before, although more than 70% claimed that traffic routes are more complex than before.

More extended research (Nava-Gaxiola, C.; Barrado, C., 2016) presented the opinions of more than 100 air traffic controllers actively involved in one of the ACCs implementing some degree of free route, as well as opinions derived from the ATC tools they utilised for conflict and resolution. The controllers for Lisbon FRA and NEFRA exhibited more enthusiasm for the benefits and future of free route. It is also worth noting, however, that Lisbon controllers negatively graded the tools as being limited to short-term collision avoidance, which may not be the most suitable for FRA sectors.

In conventional airspace, all aircraft follow the fixed and known route structure. During their training, ATCs memorise most of the usual flows of their qualified sectors. In those flows, aircraft move forward following an expected sequence, with some few overtakes. Flight levels are organised depending on directions, and merging and crossing points are known by experience. Moving from this to a free-route organisation breaks many such rules and memories. A more chaotic ATC screen, with aircraft at unexpected locations, is currently being managed when traffic is light. In order to extend FRA benefits to new areas and new opening times, suitable tools must be developed and tested. Participation of the ATC is crucial to obtain effective solutions to forthcoming FRA challenges.

2.6.6. PRU Complexity

This PhD thesis utilises the Eurocontrol complexity score (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006) as the airspace complexity indicator.

The notion of an interaction represents the key concept arising from this work on complexity. It is the presence of several aircraft in the same area that generates complexity, particularly if those aircraft are in different flight phases or possess different headings or speeds.

Within this study, an interaction is defined as the simultaneous presence of two aircraft in the same cell viewed from each aircraft's perspective. In Figure 2.13, cell k possesses two interactions and cellk+1 features six interactions. Each interaction takes place between two and only two aircraft.

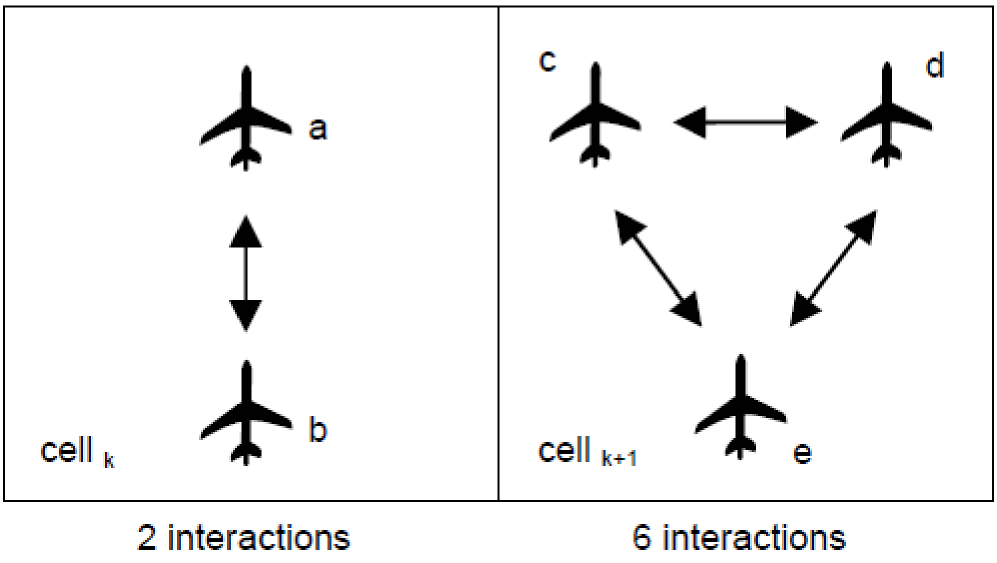

Figure 2.13 Interactions. Source: (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006)

As this study employs a macroscopic view, it examines potential interactions and not actual interactions. The indicators do not seek to capture the actual number of interactions that occurred on a day, but rather the probability of interactions arising from the traffic flows.

The method also only studies how long each aircraft remains in the cell during the hour and considers that each aircraft may have passed through the cell at any time during the hour. In these conditions, if ta and tb describe the recorded durations of aircraft (a) and (b) in the cell during the hour, then the expected duration (in hours) of the interaction between aircraft a and b is equal to the product ta x tb.

So, the expected duration of one interaction between two aircraft, each of which spend three minutes in the cell (1/20 of one hour), is presented in Equation 1:

Equation 1

$$\left(\frac{1}{20}\times\frac{1}{20}\right)=\frac{1}{400} \text{ or } 0.0025 \text{ hours}^{5}$$

If the two aircraft in cell k each spend three minutes in the cell, then the expected duration of the interactions (a with b and b with a) during the one-hour period is presented Equation 2:

Equation 2

$$2\times\left(\frac{1}{20}\times\frac{1}{20}\right)=\frac{1}{200} \text{ or } 0.005 \text{ hours}$$

If each aircraft spends three minutes in cellk+1, the expected duration of the six interactions is described in Equation 3:

Equation 3

$$6\times\left(\frac{1}{20}\times\frac{1}{20}\right)=\frac{3}{200}\ \text{or 0.015 hours}$$

These calculations are performed for each pair of aircraft in a cell, and the sum of the durations provides the hours of potential interactions for that cell.

Two main metrics define the complexity score: adjusted density and structural index. The structural index is derived from three other metrics of the potential number of conflicts in specific situations classified as vertical, horizontal and a mix of aircraft performances. The term 'potential' refers to the probability that the coincidence of two aircraft in an area may occur during a one-hour period.

The potential interactions can experience additional complexity if they involve aircraft in evolution (vertical interaction or VDIF), in horizontal flights for headings possessing more than 30 degrees of difference (HDIF) and/or combining aircraft with different performances (SDIF) (see Table 2.5).

Table 2.5 Complexity score indicator components (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006)

Dimension	Metrics	Description
Traffic density	Adjusted density (AD)	Potential number of interactions per volume of airspace
Traffic evolution	Potential vertical interactions (VDIF)	Potential interactions between climbing, cruising and descending aircraft (< 500 ft)
Flow structure	Potential horizontal interactions (HDIF)	Potential interactions based on the aircraft headings (> 30°)
Traffic mix	Potential speed interactions (SDIF)	Potential interactions based on the aircraft (> 30 kt)

This PhD's calculations consider an airspace volume in 3D cells with dimensions of 20 NM x 20 NM x 3000 ft. Twelve shifts of 10 NM horizontal and/or 1,000 feet vertical are applied to the 3D cells' grid and the mean of the obtained results to avoid frontier concerns.

The complexity is computed separately for each cell and for discretised 60-minute periods, after which it is finally averaged.

Adjusted Density

The adjusted density is defined as the quotient of two time periods: the duration of all potential interactions and flight hours. The potential interactions are measured for each pair of aircraft and from each aircraft's point-of-view.

For instance, if two aircraft reside in the same 3D cell, this will incur a total of two interactions (each of the two aircraft present interact with the other aircraft), while a 3D cell with three aircraft will generate six interactions.

The duration of a potential interaction (in hours) is calculated as the total number of potential interactions multiplied by each involved aircraft's time inside the 3D cell.

Finally, the total flight hours in the cell equals the sum of the flight segments' duration for all the aircraft crossing the cell during the hour period.

Structural Index

Structural index depends on three types of complex interactions: horizontal, vertical and speed. The horizontal interactions (HDIF) assess a pair of aircraft according to their relative headings. Only pairs of aircrafts with a difference greater than 30° headings are considered.

The vertical interactions (VDIF) measure only the interactions occurring when aircraft in a climbing or descending phase possess vertical speeds differing by more than 500 fpm, including situations in which one of the aircrafts is in cruise.

Finally, the speed interactions (SDIF) provides a value for the mix of aircraft types. It considers pairs of interacting aircraft only if their different speed performances exceed 35 kt in nominal cruise. The HDIF, VDIF and SDIF expressions are provided in Figure 2.14.

HDIF = duration of potential horizontal interactions / total flight hours in cell

VDIF = duration of potential vertical interactions / total flight hours in cell

SDIF = duration of potential speed interactions / total flight hours in cell

Figure 2.14 Horizontal, vertical and speed interactions

The previous indicators are transformed to relative indicators through the equations described below in ¡Error! No se encuentra el origen de la referencia. These relative indicators can be interpreted as the percentage of potential interactions that are vertical, horizontal or due to the speed differences.

An interaction can be classified in more than one type, and so the sum of the indicators can be greater than 1. This sum represents the definition of the structural index and provides a macroscopic view of the complexity of the set of traffic flows in the area. The maximum would be 3 if every interaction met all the criteria (see Figure 2.15).

$$R_{VDIF} = VDIF \,/\, Adjusted\ density$$

$$R_{HDIF} = HDIF \,/\, Adjusted\ density$$

$$R_{SDIF} = SDIF \,/\, Adjusted\ density$$

$$Structural\ index = R_{VDIF} + R_{HDIF} + R_{SDIF}$$

Figure 2.15 Relative indicators

Complexity Score

Finally, the structural index and adjusted density are combined as in Figure 2.16 to obtain the generic aggregation, called the complexity score.

The complexity score provides a general overview of a specific airspace's complexity and traffic conditions by considering the main two issues affecting complexity: adjusted density and structural index.

$$Complexity\ score = Adjusted\ density \times Structural\ index$$

Figure 2.16 Complexity score

2.6.7. ATC Controller Taskload

Research on air traffic metrics has historically been conducted in two main areas: safety and capacity, both of which are highly interrelated. For safety, the main indicators are the number of occurrences of aircraft separation violations, collision avoidance alerts and incidents. All of these represent *posteriori* indicators, which can rarely be anticipated and usually involve abnormal situations, such as human errors, aircraft contingencies, strong weather conditions or ATM system failures (Vogel, 2013).

As an *a priori* safety measure, capacity is applied in Europe as part of its safety net, but, despite upgrades in onboard systems, humans still constitute the core of the ATM system. Thus, the capacity is largely determined by the controllers' workload (Majumdar, 2005). Unfortunately, the ATC workload represents a subjective value and can only be measured during the ATC activity. Simulations have thus been frequently used to assess the workload limits. Finally, experience is also employed to fix a capacity to each sector. Admitting several aircraft in a sector above its capacity is considered unsafe, and delays or re-routings are applied to avoid this.

In a *posteriori* assessment, capacity indicators compare the aircraft entry counts with the capacity. An entry count at 80% of the capacity is considered convenient. Higher values can compromise safety if overly prolonged, while lower values are considered inefficient regarding ATM resources.

A long list of works have developed matrices for measuring the work- or taskload of controllers, especially for ANSP and capacity calculation. For instance, Welch (Welch, 2013) proposed a full workload model to be used by an ANSP in deciding sector capacity in case of weather events. This model applies regression across an extensive list of metrics related to ANSP including aircraft count, traffic peaks, throughput (aircraft per hour), weather, task recurrences, mean transit time, and size of the sector volume. The model has been revealed to predict capacity more accurately in all weather conditions.

Based on their contribution to total variance of regression analysis, Vogel (Vogel, 2013) selected 19 complexity metrics and combined them into six aggregated super-factors to predict controller workload and collision risk using dynamic density themes.

Relating free route and ATC workload from Eurocontrol, another study (Bucuroiu, 2017) mentioned that free-route implementation provides some benefits for ANSP, all of which concern ATC workload, such as not expecting any impact on ATC workload or even, in some cases, anticipating reduction in this issue. Another important point of note is that no ATC workload increment issues were identified in any of the ACCs operating FRA over the past nine years, nor any additional bottlenecks.

3. Free-Route Airspace Simulations

This chapter describes the metrics and parameters employed in the simulation stage of this thesis. Simulations include multiple airspace scenarios under free-route implementation, with each scenario and metrics associated with flight efficiency and potential separation losses (conflicts). Furthermore, airspace complexity metrics are measured to understand how FRA airspace configurations affect the ATM system. The simulations process is summarised in the following figure, where the three steps involved are clearly defined.

The first stage involves the metric definition (see Figure 3.1). The selection of the metrics being employed is based on the background discussed in chapter two. Through this stage, the parameters describe the characteristics and conditions for all simulations.

Then, the second stage centres on all data required for simulation running. The combination of both scenario and traffic sample enables running the simulation tool (NEST), as described in the final part of this chapter.

Scenario generation involves airspace design (changes in waypoints, flight levels, airspace blocks borders, etc.), retaining the current and past configurations to analyse the next stage. The traffic sample is filtered, limiting the trajectories' flights to the defined parameters. With all this, approximately 25.00–30.000 trajectories are processed for simulations.

The third stage is based on metric calculation and analysis. This stage demands high computer effort, because the scenario and data proposed in this PhD thesis involves a high number of flight trajectories. Combining those trajectories with the new scenarios, is it possible to produce new conditions derived from free route, as this thesis is searching for.

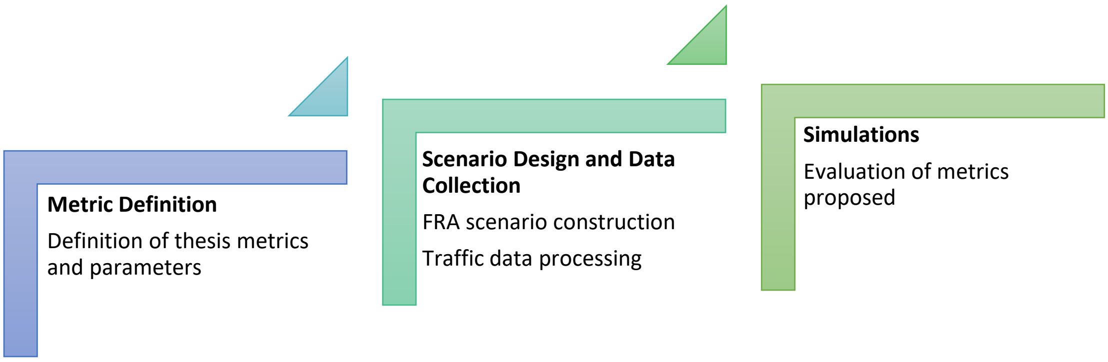

Figure 3.1 Simulation process

The detailed simulation process is defined in APPENDIX B – Simulation Process of this thesis.

3.1. Simulation Metrics

The detailed metrics considered in this thesis are grouped into three areas. The first set of metrics links flight efficiency with route length and flight time. These parameters are seeking deviations and route extensions by detecting inefficiencies between original and simulated trajectories with the proposed scenarios.

The second metric specifically focusses on detecting possible separation losses according to the conditions of the protected zone of each aircraft simulated. The measured conflict parameters are explained in section 3.1.2 of this chapter.

Together with the last metric, a third set of parameters provides information concerning how complex the airspace is becoming with the evaluated FRA scenarios and traffic samples.

The diagram presented in Figure 3.2 offers a general idea of each metric evaluated in this thesis:

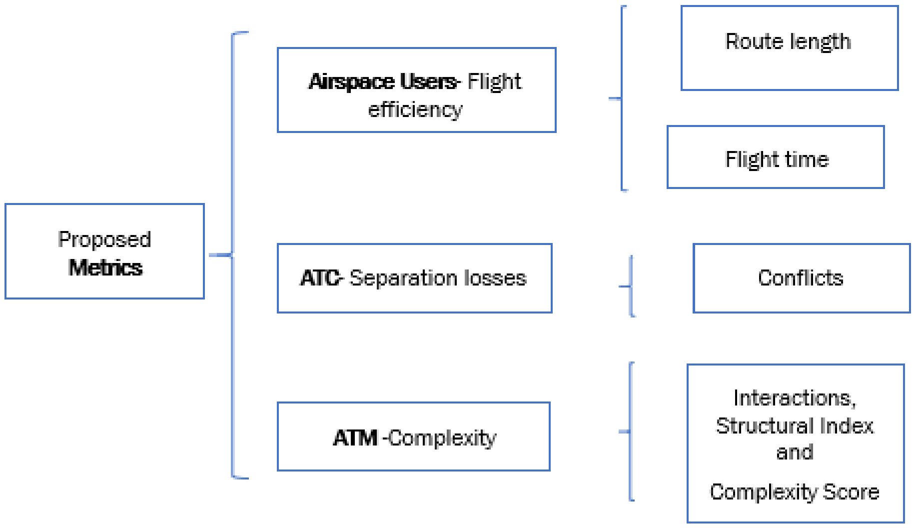

Figure 3.2 Summary of thesis metrics

3.1.1. Flight Efficiency Metrics

Flight efficiency involves evaluating the benefits or drawbacks that free-route implementations produce for airspace users, such as airlines and aircraft operators. As previously mentioned, three parameters are evaluated: route length, flight inefficiency and flight time.

Route Length

The parameters 'route length' and 'flight inefficiency' offer a broad analysis of the route extensions with the goal of assessing network efficiencies. The route length computation employs a spherical Earth model. The following table (Table 3.1) illustrates the parameters considered in this calculation.

Table 3.1 Route length and flight inefficiency metrics

Route length	Differences between actual and free-route trajectories (NM)
Route inefficiency	Percentage of route length differences (%)

Regarding the route length metric, this only covers the en-route segment of the route; it does not consider the TMA route segment in the route length computation. To do so, it subtracts a fixed route length corresponding with the lower trajectory, which remains beyond the scope of this study.

As the parameter for route length calculations, this thesis considers the route flown by the aircraft (average route length in the CFMU model).

The CFMU models relate to realistic aircraft behaviours in ATC simulations with the goal of improving the aircraft behaviour model in its large-scale and real-time ATM simulation system by identifying specific aircraft operation parameters from historical radar data.

Flight Time

Another metric related to the flight efficiency simulation involves the flight time (see Table 3.2), the process for which is based on the total flight time in hours and the number of flights for each airspace present in the related files (actual or free-route trajectories).

Table 3.2 Flight time definition

Flight time	**Total flight time in hours for flight trajectories**

With all these metrics—route length, route inefficiency and flight time—this thesis makes it possible to identify the changes and benefits from the airspace user perspective.

3.1.2. Number of Conflicts

From the ATC perspective, the number of potential separation losses between trajectories is defined as ‘conflicts’. Specifically, the metric evaluated in this simulation stage is oriented towards providing an indication of conflicting traffic within a traffic sample (see Table 3.3).

Table 3.3 Conflict definition

Conflicts	**Number of possible separation losses regarding vertical and horizontal distances**

To obtain the number of conflicts, a group of parameters are considered during simulations:

- Uncertainties frame: As aircraft may not always take off on time, the user may input deviation values to take this into account. Several runs may be performed with the same traffic sample: The first run utilises the quoted departure time, whereas subsequent runs distribute the aircraft along a Gaussian normal curve where the user can change both the average and standard deviation.
- Calculation step field: This defines the time interval at which the calculation is performed.
- Number of runs for each traffic sample.
- Average delay: The average delay applied to all aircraft in seconds.
- Standard deviation: In this case, a high percentage of all aircraft will be delayed within this time frame in seconds.
- Vertical separation: This determines the vertical separation.
- Horizontal separation value: This defines the horizontal separation minima.

To achieve a conflict simulation, it is necessary to define each of the previously described parameters; in this sense, the next table (Table 3.4) illustrates the values used for all conflict simulations:

Table 3.4 Conflict parameters

Dimension	Parameter	Value
Uncertainties	Calculation step	10 seconds
	Number of runs	10
	Average delay	120 seconds
	Standard deviation	120 seconds
Distance	Vertical separation	RVSM (1000ft)
	Horizontal separation	5 NM

Once the conflict simulations are complete, the expected results in terms of conflicts are oriented so that the different conflict scenarios of each traffic sample can be studied.

Conflicts between traffic samples can be organised according to the dimension in which the separation loss is produced: vertical, horizontal or evolving. Furthermore, conflicts can be distributed in the horizontal dimension by conflicts of parallel, opposite and crossing trajectories.

Finally, the combination of all types is summarised in the following combinations:

- Evolving / Evolving Parallel
- Evolving / Evolving Opposite
- Evolving / Evolving Crossing
- Evolving / Cruise Parallel
- Evolving / Cruise Opposite
- Evolving / Cruise Crossing
- Cruise / Cruise Parallel
- Cruise / Cruise Opposite
- Cruise / Cruise Crossing

With a categorisation of conflicts type, it is possible to view the increments and conflicting scenarios produced by introducing FRA.

3.1.3. Complexity Parameters

From the ATM point of view, the simulations evaluate complexity indicators, as based on section 2.6.6 in the previous chapter. To this end, the PRU complexity model (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006) is oriented towards computing a set of complexity indicators and providing an overview of traffic complexity related to a specific airspace—in this case, to FRA.

The simulated indicators are based on the concept of 'interaction', which is defined as the simultaneous presence of two aircraft in an airspace cell. Interactions indicate that complexity is generated by the simultaneous presence of several aircraft in the same area, particularly if those aircrafts are in different flight phases and/or possess different headings.

The indicators do not focus on actual interactions, but rather on potential interactions between flows of aircrafts during one-hour periods. This provides a macroscopic view of traffic complexity.

Grid Cells

The PRU complexity model used for simulation splits the total airspace volume in three-dimensional cells of equal volume, defined as 20nm x 20nm x 3000ft. The complexity indicators are computed separately in each cell, enabling easy aggregation at ACC and ANSP levels.

The data on traffic within each cell are collected during discrete 60-minute periods. So, a one-day simulation features 24 data sets for each cell. Two aircraft entering the same airspace cell during the same time frame are also considered interacting with each other.

Complexity Parameters

Interactions are counted for each pair of aircraft and from each aircraft's point-of-view, meaning that a cell with two aircraft will possess a total of two interactions (the two present aircraft interact with the other aircraft), while a cell featuring three aircraft will witness six interactions (each of the three aircraft will interact with other two).

The duration of interaction between a pair of aircraft is defined as the product of the durations of both aircraft in the cell (expressed as a ration of the unit of time: one hour).

This method only studies how long each aircraft is in the cell during the hour and considers that each aircraft may have passed through the cell at any time during the hour. This means that all potential interactions are considered, even if the aircraft were not simultaneously present at the same time in the cell.

The total duration of interactions in a cell is defined as the sum of the duration of interactions of each pair of aircraft interacting within the cell. The adjusted density of a cell is computed as the total duration of interaction in the cell divided by the total flight hours registered in the cell.

The **VDIF**, **HDIF** and **SDIF** indicators are computed in a similar manner, but considering only the interactions respecting the conditions defined for each of them to compute the total duration of interactions:

Table 3.5 presents a summarised description of each of the complexity parameters employed in simulations:

Table 3.5 Complexity indicators definition

Complexity parameter	Description
Adjusted density	Total duration of interactions / flight hours
Vertical indicator	Total duration of vertical interactions / flight hours
Horizontal indicator	Total duration of horizontal interactions / flight hours
Speed indicator	Total duration of speed interactions / flight hours

To simplify the analysis, a set of **relative indicators** is proposed for each dimension. These values can also be interpreted as the percentage of interactions that are vertical, horizontal or due to speed differences:

- **r_VDIF** = VDIF / Adjusted density
- **r_HDIF** = HDIF / Adjusted density
- **r_SDIF** = SDIF / Adjusted density

Then, the traffic flow structure can be represented by the **structural index** indicator:

- **Structural Index** = r_VDIF + r_HDIF + r_SDIF

Finally, the structural index and adjusted density are combined in an aggregation called the **complexity score**:

- **Complexity Score** = Adjusted Density x Structural Index

During the simulation process, the complexity indicator results are grouped by evaluated airspace and flight levels.

Complexity indicators of a given airspace are available for each step of 10 FL, beginning at the average level of the grid's first cell where flight interactions have been encountered in the airspace (usually 100FL).

3.2. Traffic sample extraction

This thesis further evaluates multiple traffic samples, all concerning **six airspace scenarios** (see Figure 3.6).

The traffic data is obtained from Eurocontrol (Eurocontrol, Demand Data Repository, 2019), and all traffic data are generated from flight plans filed by aircraft operators. Three 'types' of traffic data, or trajectories, are present (Eurocontrol, NEST User Manual, Version 1.6, 2018):

1. Initial trajectory (FTFM or M1 in NEST terminology) is based on the last filed flight plan. The NEST term 'initial flight plan' should not be confused with the first filed flight plan from aircraft operator. In reality, an aircraft operator could file an FPL and then update or change it several times. Such an FPL change log is not available for download, but only the last filed FPL.
2. Regulated trajectory (RTFM or M2 in NEST terminology) is the same as the initial for nonregulated flights. For flights subject to regulation(s), the most penalising ATFM delay is added, thus changing time component of their trajectories.
3. Actual trajectory (CTFM or M3 in NEST terminology) describes the initial trajectory updated with available radar information whenever the flight deviates from its last filed flight plan by more than any of the pre-determined NMOC thresholds (5 minutes, 7FL or 20NM).

   This trajectory represents the closest estimate available in official NEST data files of the flight trajectories handled by controllers on the day of operations.

The DRR data is obtained according to Figure 3.3, with illustrates the numerous stakeholders involved in the traffic samples, including aircraft operators or flight plan offices, ANSPs, the STAFOR prognosis team, airports, network managers, and more.

Figure 3.3 DRR sources (Eurocontrol, NEST User Manual, Version 1.6, 2018)

Considering all these conditions, this thesis utilises **traffic samples M1 or FTFM trajectories**, and all are extracted from the DDR repository.

3.2.1. Flight Increase Process Simulator

To complete the study, this thesis employs the **Flight Increase Process Simulator**, or FIPS, which is an algorithm based on using a current traffic sample to convert traffic forecasts into future traffic samples.

Here, flights are added and removed randomly to maintain existing traffic patterns while respecting system constraints such as airport capacities and curfews. In this sense, the FIPS algorithm works with traffic forecasts expressed as percentage increases at the OD (Origin-Destinations) zone level.

The next figure (Figure 3.4) provides an overview of the FIPS algorithm, and thus, as can be seen, the FIPS algorithm incorporates an important input from the STATFOR forecast.

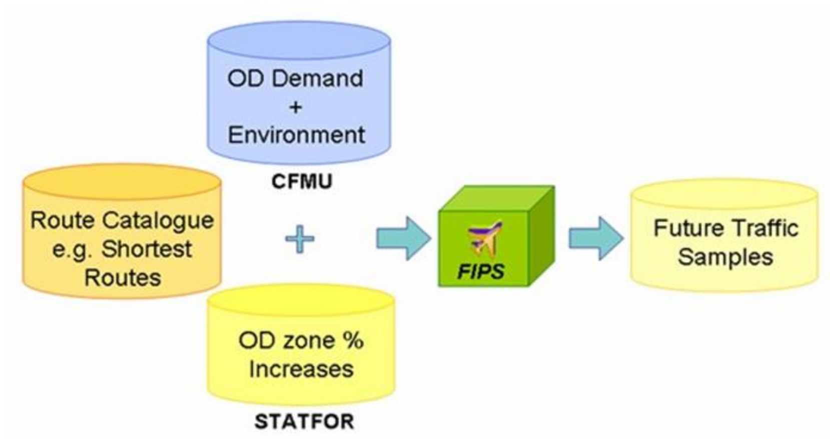

Figure 3.4 FIPS (Eurocontrol, NEST User Manual, Version 1.6, 2018)

3.2.2. STATFOR Forecasts

The thesis utilises several traffic forecasts, all of which were generated by the FIPS algorithm in base STATFOR medium-term forecasts.

According to theory (Eurocontrol, NEST User Manual, Version 1.6, 2018), the STAFOR forecast indicate the percentage increase for airport pairs by looking seven years ahead and build on the short-term forecasts. The medium-term forecasts combine flight statistics with economic growth models of other important drivers in the industry, such as costs, airport capacity, passengers, load factors, aircraft size and so on.

The STATFOR is based on origin-destination (OD) zones. As is illustrated in the following figure, the STATFOR high medium-term forecast for these zones is presented in yellow. Here, the input data includes today's demand for these OD zones, the high STATFOR growth hypothesis and a route network scenario.

The example explained in Figure 3.5 considers seven years into the future using the future shortest route network.

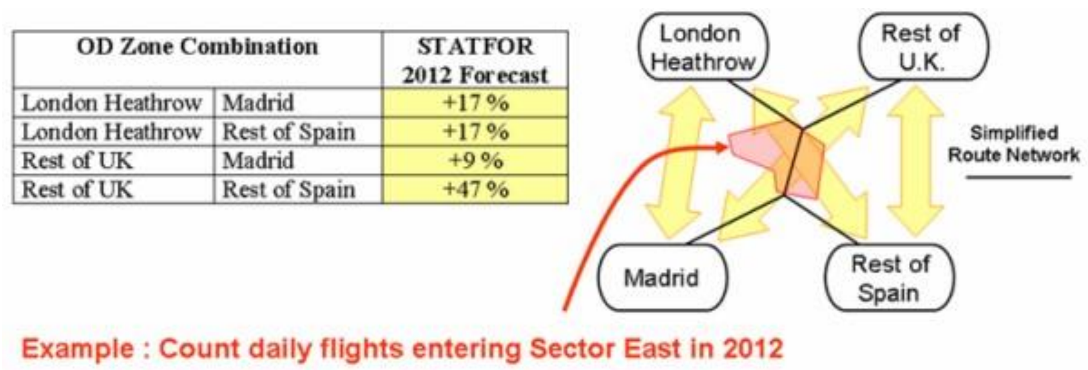

Figure 3.5 Example of STAFOR forecast with NEST

The STATFOR philosophy is primarily used for increases or decreases to each daily demand of the current scenario. This is the random flight cloning process. This process involves a complex algorithm where flights are randomly selected for cloning whilst simultaneously respecting airport curfews, capacity constraints and STATFOR increases.

In cases of a demand increase, flights to clone are randomly selected among all the initial flights departing during the day so that the peaks of departures are increased as a highest priority. For the case of a demand decrease, the departure period is randomly selected in a first step, while flights to remove are randomly selected from inside the selected period in a second step, thereby ensuring that existing peaks are maintained.

This difference of behaviour between demand increase and decrease reflects the economical preference of airline actors, for which departure peaks correspond to the most valuable period of the day.

3.3. Proposed Scenarios

The thesis evaluates three perfectly defined scenarios and their respective situation with free-route operations, providing a total of six simulation environments.

For simplicity, Figure 3.6 depicts the scenarios contemplated for assessment:

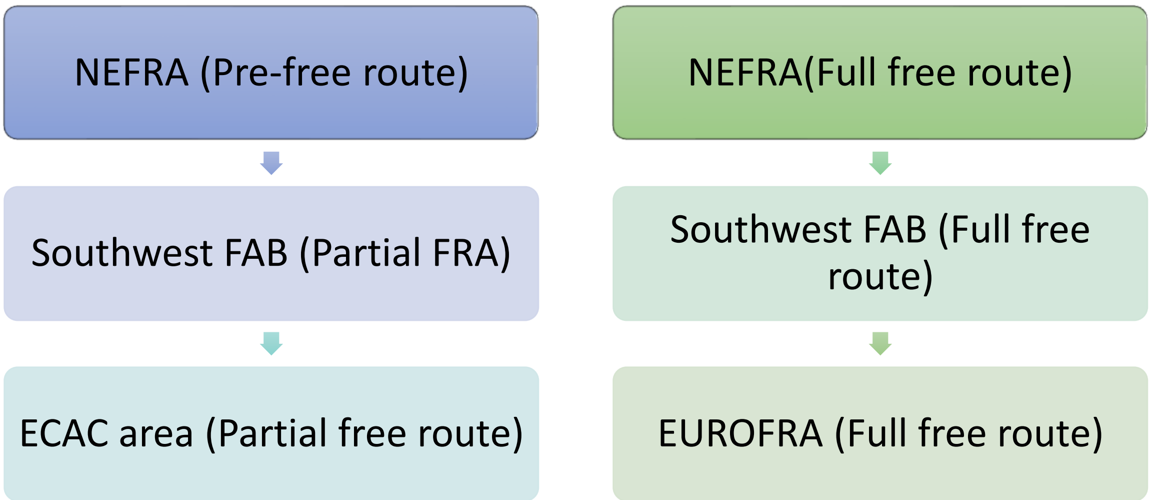

Figure 3.6 Scenarios generated for simulations

3.3.1. North European Free-Route Airspace

The first proposed scenario (see Figure 3.7) is based on the North European Free-Route Airspace (NEFRA) programme, established on 11 March 2013. It is formed by six states of two FABs, Denmark-Sweden (DK/SE FAB) and Norway, Finland, Estonia and Latvia (NEFAB), which signed a declaration of commitment in airspace development. In doing so, they committed themselves to undertaking necessary actions to ensure implementation of the FRA concept above FL 285 in the joined airspace, named NEFRA.

In the Norway airspace, BODO oceanic is considered a part of the ICAO NAT (North Atlantic Region). The study by Holstila and Andersson (Holstila & Andersson, s.f.) illustrated details of the work performed to design and implement NEFRA after a consultation process involving 18 stakeholders.

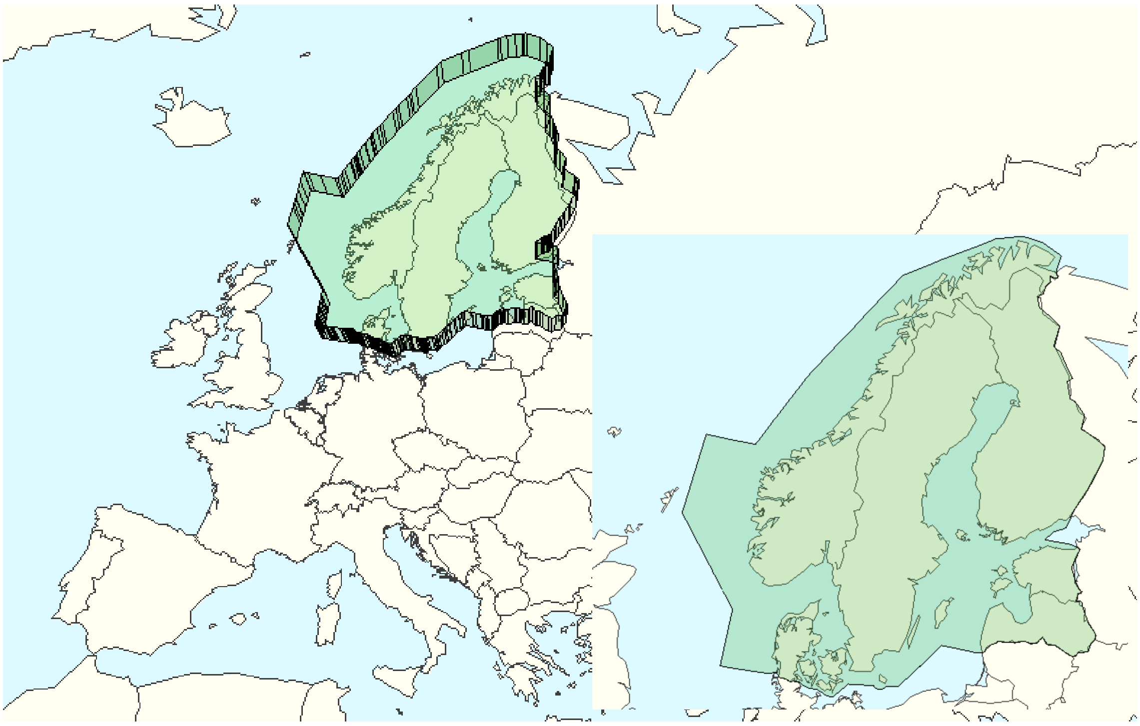

Figure 3.7 NEFRA area used for this study.

Over 3200 flights cross NEFRA every day. Due to its geographical location, NEFRA is used as a bridge to the East for flights between Europe and Asia, and to the West to connect North European flights with North America.

The full NEFRA plan will be completed in 2020 when NEFRA evolves to the Borealis FRA and offers joint FRA from FL285 to FL660 of all six countries. However, before the programme started, each of the ANSPs participating in NEFRA already possessed plans to implement the FRA concept following different approaches.

The diversity of the lower limits established for each FRA range from the FL95 of former joint FRA between Finland, Estonia and Latvia to the FL285 of the FRA in DK/SE FAB. In between Norway, two FRAs are defined, one on the continental airspace with a lower limit in FL135, and a second in the oceanic airspace over FL195.

In consequence, the NEFRA project is planned to develop in stages spanning the pre-NEFRA stage starting in 2011 until the ultimate full integrated NEFAB, and passing through the actual inter-FAB free route block currently active as NEFRA. NEFRA includes the following ACCs: EFIN (Finland), ESAA (Sweden), EKDK (Denmark), EETT (Estonia) and EVRR (Latvia).

The scenario proposed for this thesis consists of the **NEFRA area working with a completely free route**, considering the current situation **(Oct 2018).** Furthermore, for comparison, the **previous scenario** corresponds with the airspace configuration from **2012**, where NEFRA has not been yet implemented.

3.3.2. Southwest Functional Airspace Block

The second scenario proposed in this thesis (see Figure 3.8) centres on the Southwest Functional Airspace Block (SW FAB), part of the nine FAB programmes in Europe. The FAB implementations consist of long-term plans focussed on ANS optimisation and more flexible solutions for aircraft operators.

It is important to consider the SW FAB because it represents one of the strategic FABs due to its geographical situation, making it one of the most important interconnection nodes for the American transatlantic flights and the European Norther-Southern corridor.

The SW FAB airspace forms the natural gateway to Central and South America. The SW FAB airspace also plays an important role in the European and international air transport, comprising the main link between Europe and a community of more than 400 million inhabitants with increasing travelling requirements (SW FAB , 2019).

Implementing FRA in the SW FAB is planned to conclude in 2020, and the regions and FIRs to be included are presented in the following figure:

Figure 3.8 Southwest FAB full FRA implementation 2020 ((SW FAB , 2019)

The Portugal-Spain FAB aims to fulfil the SES requirements by enabling the expected traffic growth, reducing environmental impact, continuously improving safety and enhancing cost efficiency. Furthermore, the SW Portugal-Spain FAB has been defined in accordance with the stakeholders' expectation. As a result, an operational plan (SW FAB Operational Board, 2015) was developed and maintained in order to enact the guidelines in airspace changes.

The SW FAB operational plan includes several projects related to network improvements, new cross-border configuration between Spain and Portugal, reorganisation of parallel routes between the Iberian Peninsula and Canary Island that utilise Morocco airspace, and more. The most important project concerns FRA implementation, which will enable creating the largest free-route area in Europe (SW FAB , 2019).

The operational plan defines three FRA phases: Phase I (Lisbon and FRASAI airspace), lasted from 2009 to 2014. It was completed in 2015 and featured vertical limits of operations between FL 245 and FL660.

In line with the FAB's definition, SW FAB is currently involved in three operational projects with the main goal of extending the SW FAB free-route phase I:

1. Free-route extension to FABEC;
2. Free-route extension to Santa Maria Oceanic airspace;
3. Free-route extension to Casablanca airspace (third country in the ANSP collaboration).

The next phases (Phase II and III) include Santa Maria Oceanic Airspace and Canary Islands airspace. Those phases comprise part of the long-term SW FAB airspace projects for 2020.

The **proposed scenario regarding SW FAB** considers the **current airspace from October 2018.** The next figure (Figure 3.9) presents the FIRs included in this configuration.

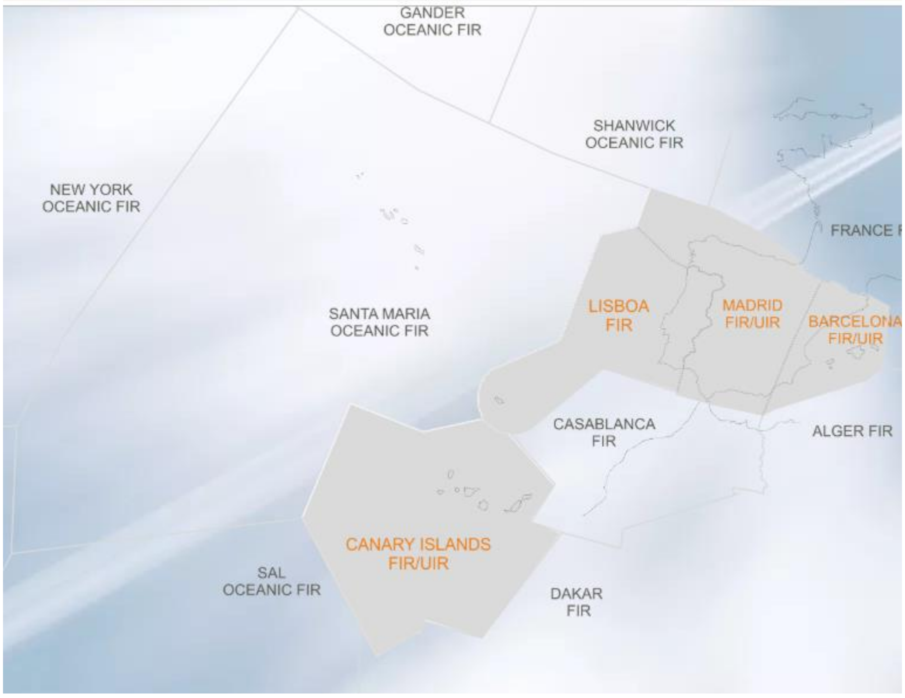

Figure 3.9 SW FAB scenario 2018 (SW FAB , 2019).

From Figure 3.9, it is important to note that the SW FAB is operating as a partial FRA, since the full implementation has not been completed. The **second scenario associated to SW FAB** and employed in this thesis corresponds with the SW FAB airspace before 2018, **when FRASAI was not implemented yet** and only Lisbon FIR was operating with free route.

3.3.3. EUROFRA

The third scenario proposed in the simulation stage corresponds with the ECAC area extension over a map (see Figure 3.10). This scenario, named EUROFRA, involves a futuristic environment considering all ECAC areas to be operating as free route.

The ECAC covers the widest grouping of member states of any European organisation involving civil aviation. Currently, it is composed of 44 member states, as presented below:

Figure 3.10 Countries from the ECAC area (European Civil Aviation Conference, 2019)

This border was obtained using the internal shape files of the Network Strategy Tool (NEST). A shape file is a text file containing the sequence of points (latitude, longitude) that define the two-dimensional limits of the area. Then, the EUROFRA is defined as a unique airspace block for the vertical levels from FL250 to FL660. Bellow FL250, the existing airports must relate to the free-route fixes.

The creation of the arrival/departure fixes regarding free route airspace, was accomplished by defining one for each airport and then connecting them to each of the standard instrument departures (SID) and standard terminal arrival routes (STAR) of the airport. In this sense, current airports arrival and departure fixes were re-utilised.

For the sake of simplicity, and because this thesis is focused in the en-route airspace, no approximation procedures were simulated.

West of the ECAC, we found current airspace to have already been defined as a 24-hour FRA. In such cases, we used the existing fixes as EUROFRA fixes, but converting the entry/exit fixes not located in the border into intermediate fixes.

Following this, new intermediate fixes needed to be defined for the rest of the EUROFRA area. These were defined using a uniform waypoint network of 2600 intermediate fixes.

The points were located one degree apart in latitude and two degrees apart in longitude, which, in the worst case, equalled a distance approaching 60 NM. With this configuration, the segments of a flight plan defined over this grid will always remain below the 200 NM limit set by the ICAO (ICAO, Doc. 4444 AIr Traffic Management, 2016) for maximum leg distance.

Figure 3.11 illustrates the design of the border (Entry/Exit) fixes of the designed EUROFRA:

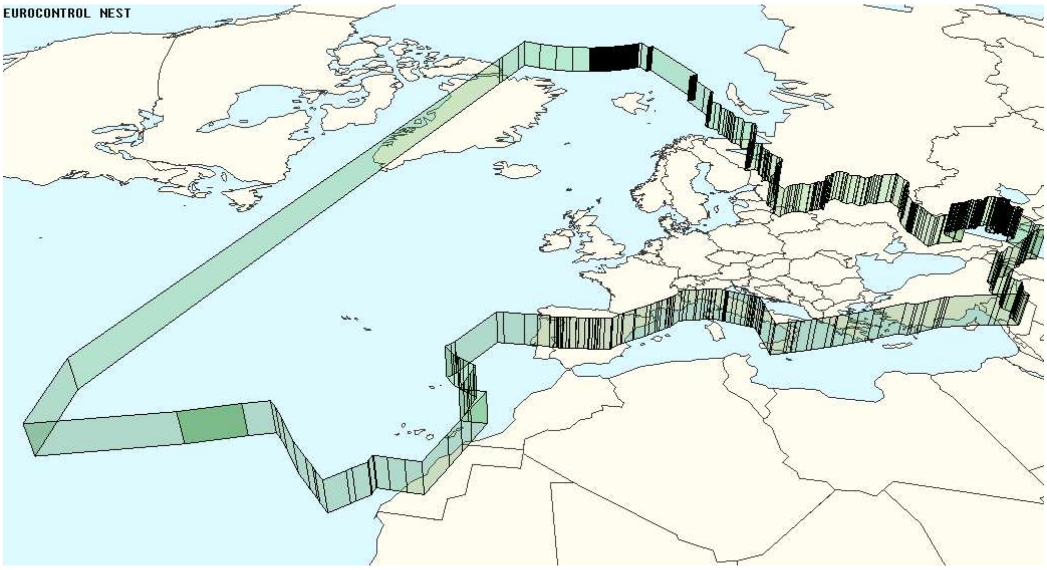

Figure 3.11 EUROFRA scenario

The scenario associated with EUROFRA is the ECAC area airspace configuration from October 2018. At the end, the EUROFRA relates traffic samples from 2024 and the ECAC region airspace with traffic samples from 2018.

3.4. Selected Traffic Sample

Table 3.6 summarises the data collected for simulations:

Table 3.6 Traffic samples

Area	Airspace	LOW Traffic (8-14 Oct 2012)	MED Traffic (8-14 Oct 2018)	HIGH Traffic (7-13 Oct 2024)
Norway, Denmark, Sweden, Finland, Leetonia and Latvia	NEFRA (2012) no free route	x	x	x
	NEFRA (2018) with free route	x	x	x
Portugal and Spain	SW FAB (2018*) partial free route	x	x	x
	SW FAB (2018) full free route	x	x	x
Europe	ECAC (2018) partial free route	x	x	x
	EUROFRA (Full free route) in ECAC area	x	x	x

From Table 3.6 it can be seen that each airspace features two scenarios, each related to the free-route implementation process. Each traffic sample also possesses thousands of trajectories—approximately 25.000–35.000, according to the applied scenario.

Related to traffic samples from 2024, it is important to note that the traffic forecast simulation interface enables specifying the FIPS traffic increase algorithm options and the list of dates where traffic will be increased.

This traffic sample simulation adds and removes flights to and from the daily flight list using forecasted OD zone traffic growth and airport capacities. The simulated traffic data resulted from traffic samples from 2018 and forecasted to 2024, as presented in this thesis.

3.5. Simulation Tool

The simulation tool employed in this thesis originates from Eurocontrol, and it is named **Network Strategic Tool (NEST).** It is primarily used in to validate new concepts related to airspace design and traffic forecast.

NEST is a stand-alone desktop application combining powerful airspace design capabilities and capacity analysis functionalities for traffic samples. The tool also offers an intuitive, planner-orientated interface with a low barrier to entry for new users. It is a powerful scenario-based modelling engine capable of running a broad range of complex, operationally relevant analyses and optimisation functionalities (Eurocontrol, NEST User Manual, Version 1.6, 2018).

Figure 3.12 presents an example of trajectories analysis using NEST.

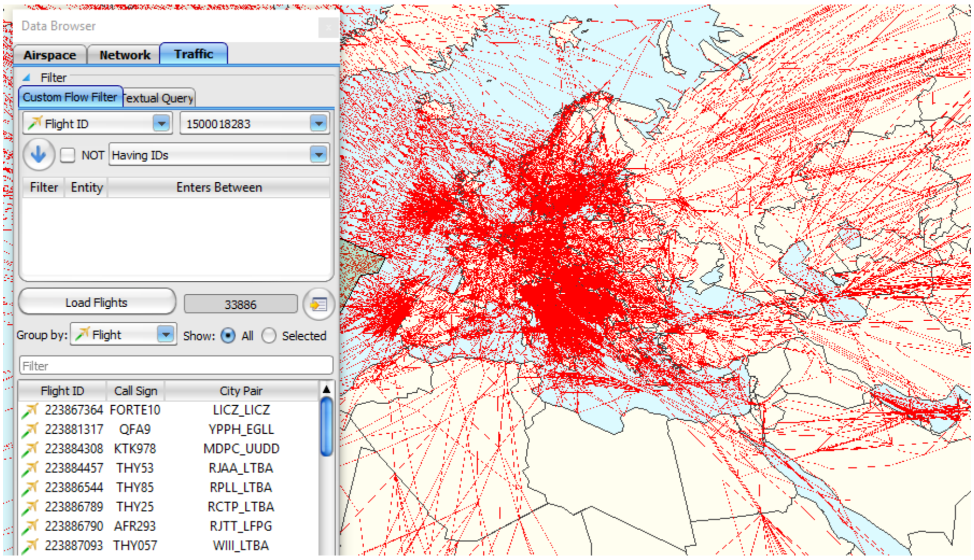

Figure 3.12 Example of trajectories analysis with NEST

Furthermore, NEST can be used locally by ACCs or airports and globally for strategic planning at the network level. The tool can process and consolidate large quantities of data spanning multiple years, but also allows the user to drill down into the details and analyse and observe 10-minute periods of data.

The algorithms included in NEST enables performance evaluations related to the following (Eurocontrol, NEST User Manual, Version 1.6, 2018):

- Future traffic samples
- 4D traffic distribution
- Configuration optimiser
- Regulation builder
- Delay simulation
- Charts
- Performance indicators

Another example of airspace design is presented in Figure 3.13:

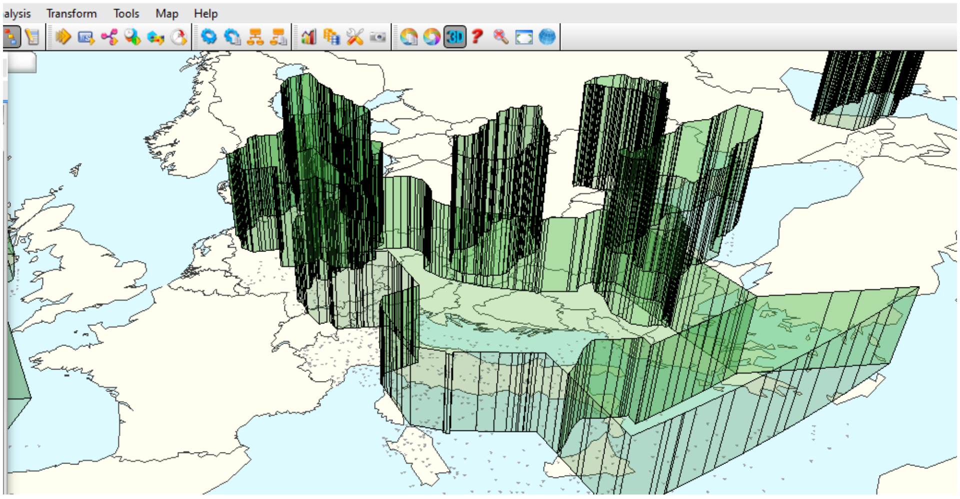

Figure 3.13 Airspace design example with NEST

4. NEFRA Airspace

This chapter presents the simulation results related to NEFRA airspace. A key aspect of this chapter involves the analysis of one of the most operated areas involving the free-route concept, and another highly important aspect concerns the number of flights and connections across Europe.

The chapter is structured as follows:

- Traffic characterisation (traffic samples)
- Route length and distance saving analysis
- Flight time and emission calculations
- Traffic conflicts
- Complexity study

4.1. Scenario Details

As described in chapter three, the NEFRA airspace is a Northern airspace that primarily supports two main traffic flows: eastern flights to Asia and western flights to North America from or to Europe.

The scenario constructed in the simulation tool is defined between FL285 and FL660. Figure 3.7 illustrates the waypoints configurations in NEST.

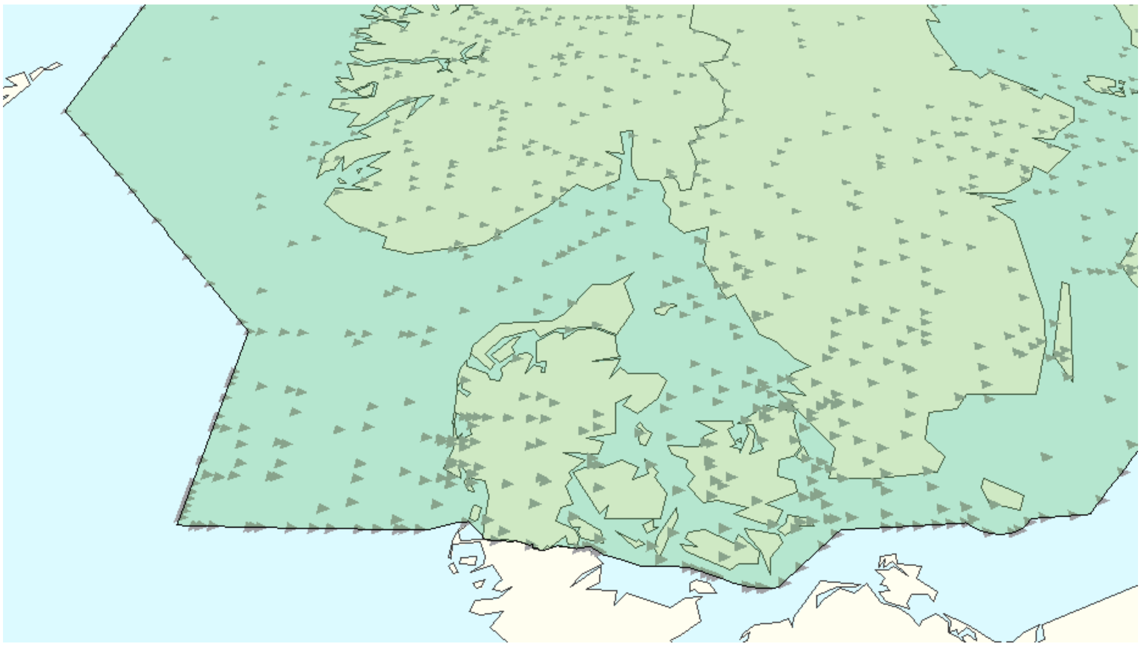

Figure 4.1 NEFRA waypoints in NEST

The waypoint configuration used for simulating includes intermediate points, entry/exit and arrival/departure points.

The downloaded airspace file (Eurocontrol, Demand Data Repository, 2019), presents some incongruences in the waypoint's border structure, however.

The airspace file consists of a text file containing the latitude and longitude points that define the limits of the area. It contains a total of 1783 waypoints, configured as follows:

- 120 Arrival (A)
- 199 Arrival and Departure (AD)
- 149 Departure (D)
- 3 Entry (E)
- 85 Entry/Exit (EX)
- 1 Entry, Exit and Intermediate (EXI)
- 1224 Intermediate (I)
- 1 Exit (X)

With this original configuration, certain entry and exit waypoints were missing. Consequently, it was necessary to complete the waypoint frontier configuration, as presented in Figure 4.2:

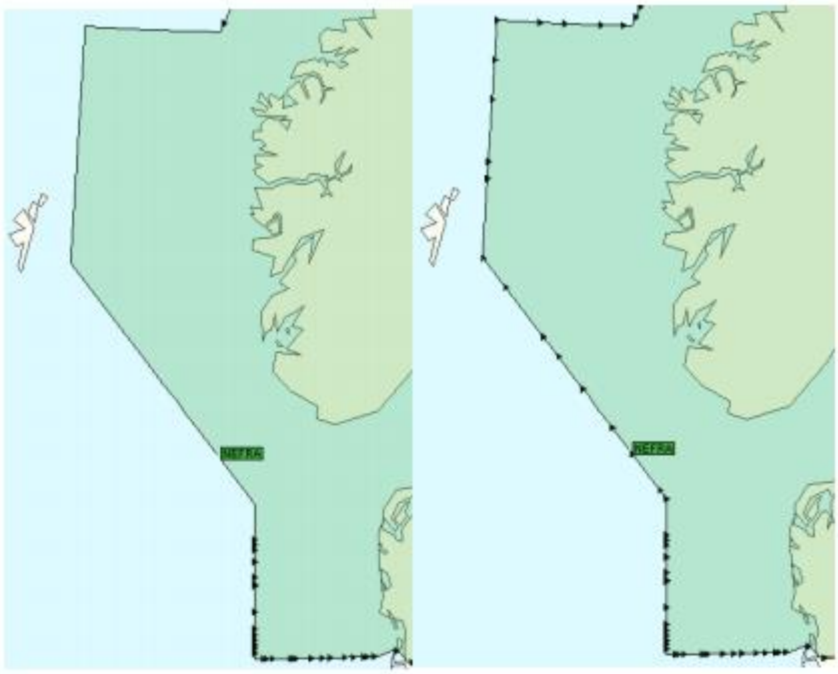

Figure 4.2 NEFRA waypoint changes

This was possible by consulting the AIP of the corresponding ANSP (Norway, Finland, Sweden, Estonia, Latvia, Denmark) (Finland ANSP, 2019), (Estonia ANSP, 2019), (Sweden ANSP, 2019), (Latvia ANSP, 2019), (Norway ANSP, 2019) and (Denmark ANSP, 2019).

All 2012 traffic samples are simulated with the real airspace configuration corresponding to 18 November 2012, which is the closest day with this information available in DDR. Similarly, 2018 traffic samples utilise the airspace configuration corresponding with 31 January 2019.

Finally, it is important to note that all the flights crossing NEFRA have been considered, with some exceptions. The flights that, in the filter data repository, crossed NEFRA and, after simulations, resulted in trajectories that did not cross have been discarded.

4.2. NEFRA Evaluation

The simulation process includes two highly differing airspace structures: one involves the airspace corresponding with NEFRA in 2012, where a partial and fragmented FRA operated with ATS routes, and this is compared against a 2018 scenario with an FRA established across the FAB.

From traffic samples, this PhD thesis considers three different approaches using traffic sample packages from one week (7 days) for each year: 2012, 2018 and 2024, as explained in chapter three.

The NEFRA scenarios are intended to determine how free-route implementation affects the Northern airspace and to compare the evolution in terms of airspace benefits, conflicts and complexity, thus providing an overview of FRA structures with multiple traffic loads.

For simplicity, the reference values regarding traffic samples in this thesis consist of media values from the seven-day traffic samples. The next section describes each sample's main and mean values.

4.3. NEFRA Results

Results from NEFRA are synthesised across several figures and graphics, where it is important to note the following aspects:

- Green bars and lines correspond to the difference between free route and initial values or not free route.
- Blue bars correspond to initial values.
- Orange bars and lines relate to the mean of presented values.
- For simplicity, a difference between free route and initial traffic is presented in percentage (%).

These representation aspects are applied for all the thesis figures and graphics.

4.3.1. SW FAB Traffic Characterisation

The thesis utilises an initial convenience traffic sample for NEFRA, with several flights extracted from de Eurocontrol DDR2 (Data repository), all from the week of October (8–14), 2012. This sample indicates a mean of 2275 flights for the seven traffic days and possesses normal distribution, lacking unusual values that exceed 243 flights of deviations between them.

The next figure (Figure 4.3) illustrates the distributions of the number of NEFRA flights in 2012.

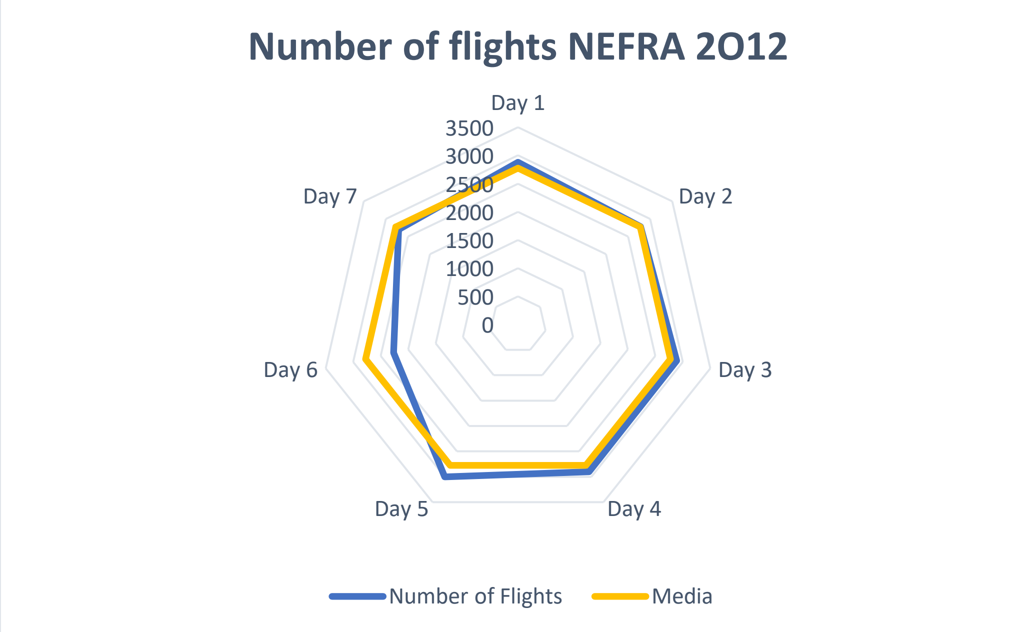

Figure 4.3 Initial number of flights from NEFRA 2012

Following Figure 4.3, the measured route length of the initial traffic samples from NEFRA in 2012 illustrate that each traffic sample possesses a mean distance flight of 3,417 million NM, as demonstrated in Figure 4.4.

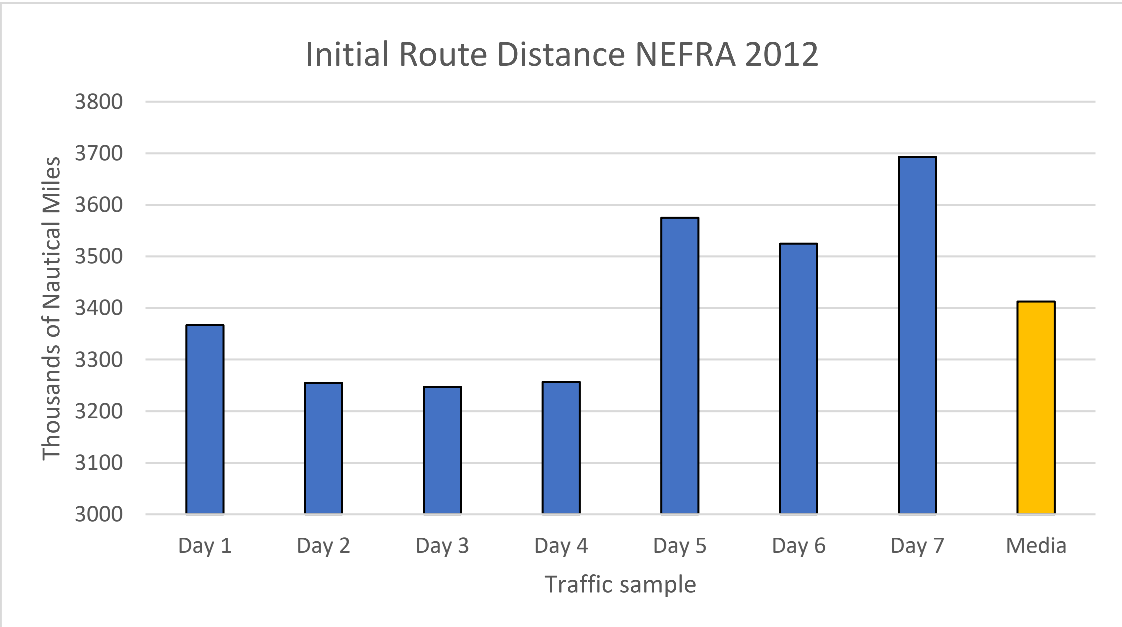

Figure 4.4 Initial route distance of flights from NEFRA 2012

For free-route trajectories, the traffic sample presents a mean of 3,413 million NM after the simulation process.

As demonstrated in Figure 4.5, the samples exhibit correlations between them, as the algorithm used in NEST does not change the flights' identity (origin, destination, type of aircraft, etc.); instead, it remains focussed on optimised trajectories using the same flight IDs.

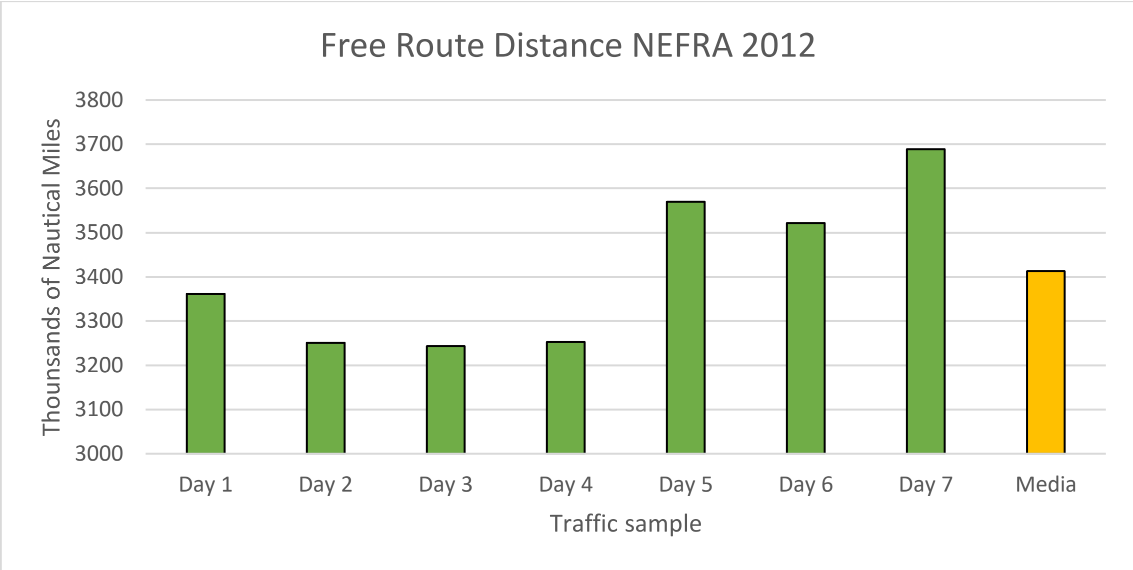

Figure 4.5 Free-route distance of flights from NEFRA 2012

The 2018 samples exhibit a notable increment in the number of flights, reaching more than 500 new flights. This increases distance calculations by approximately 1 million NM compared to traffic from 2012 (Figure 4.6, Figure 4.7).

NEFRA airspace is the smaller area of study chosen for this thesis, but the density and number of flights provides an important overview of free-route structure implementation.

Initial flights from NEFRA 2018 exhibit a mean of 3240 flights, and with a number of similitudes to the samples from 2012. It also does not illustrate important deviations between the number of flights per day, with deviation remaining less than 217 flights (see Figure 4.3).

Figure 4.6 demonstrates the initial number of flights considered for NEFRA simulations in 2018:

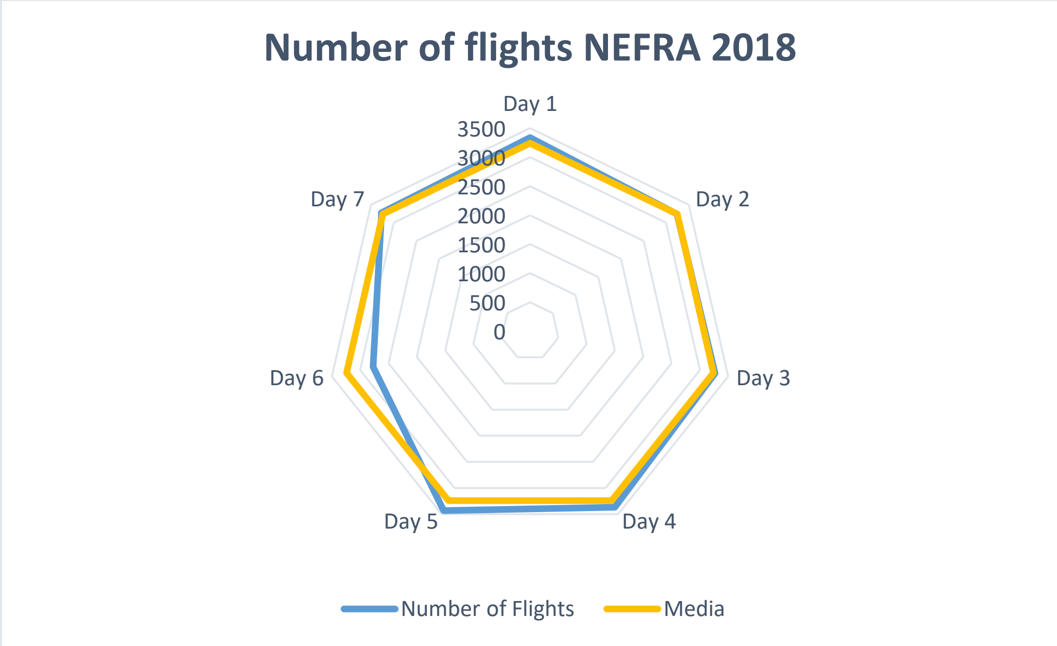

Figure 4.6 Initial number of flights from NEFRA 2018

Data from NEFRA 2018 (see Figure 4.7) indicates a mean total distance of 4,480 million NM. This represents a notable increment in traffic in only six years for the NEFRA area compared to the traffic mean from 2012.

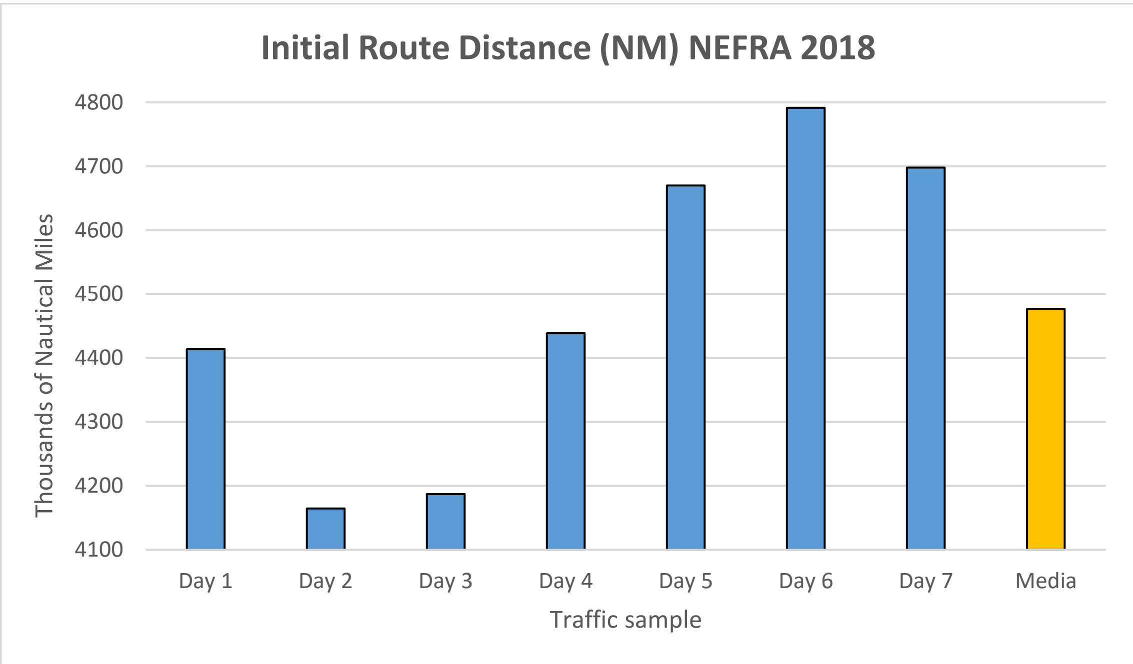

Figure 4.7 Initial distance of flights from NEFRA 2018

On the other hand, the free-route distance presented in Figure 4.8 exhibits a mean of 4,476 million NM, with the same behaviour of peak days as the initial sample.

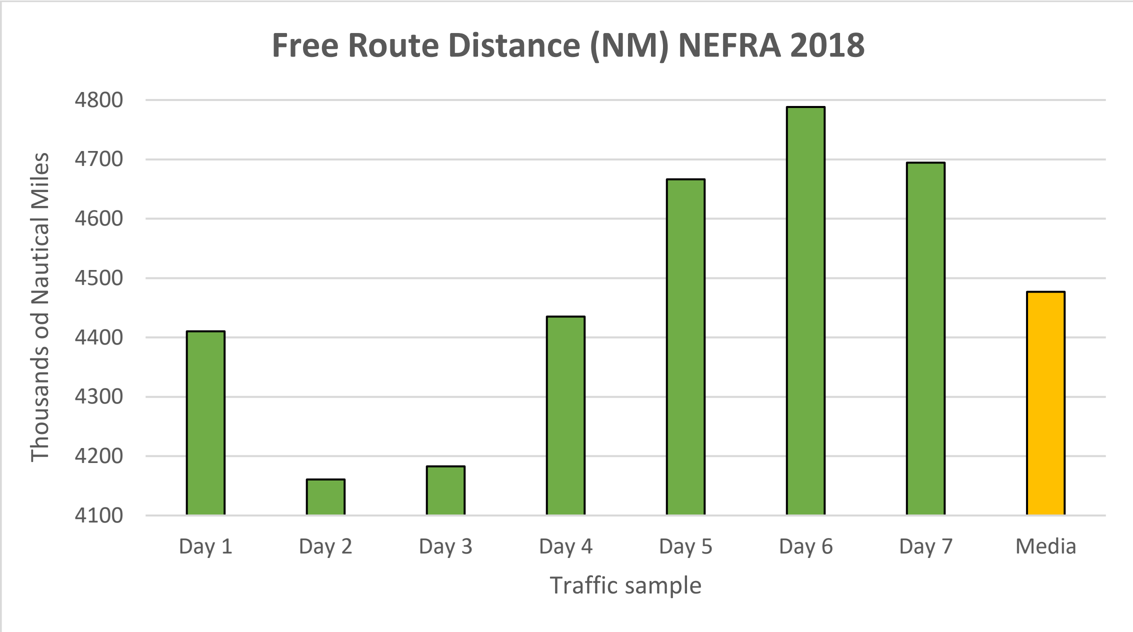

Figure 4.8 Free-route distance of flights from NEFRA 2018

The traffic prognosis used in this thesis is presented in Figure 4.9, where it is easy to compare an increment of approximately 650 flights against the 2018 scenario. Thus, the prognosis results in approximately 17% more flights.

Also illustrated in Figure 4.9, the future estimation demonstrates a low value in day seven compared to the sample's mean, which was estimated at 3890 flights.

The traffic prognosis considers numerous factors using the algorithm explained in section 3.2.2.

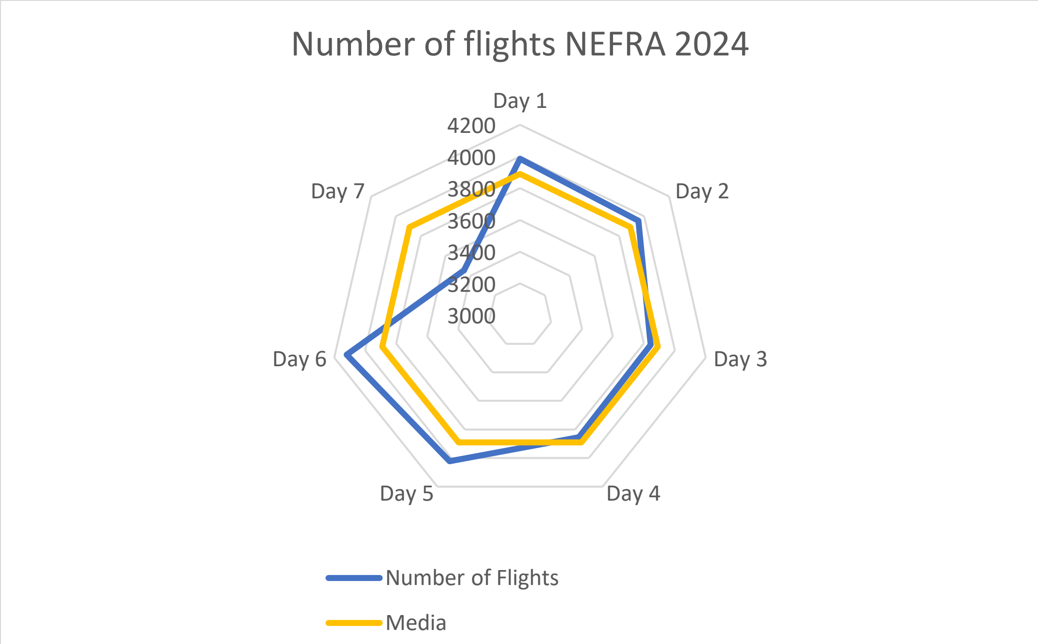

Figure 4.9 Initial number of flights from NEFRA 2024

The route distance from the 2024 samples (see Figure 4.10) feature an increment of approximately 1.3 million NM. Compared to 2018, this equals 23% more NM. The effects of this increase are evaluated around this chapter in terms of distance savings or changes in the airspace complexity values.

Figure 4.10 illustrates the distance values of each traffic sample day from the prognosis generated:

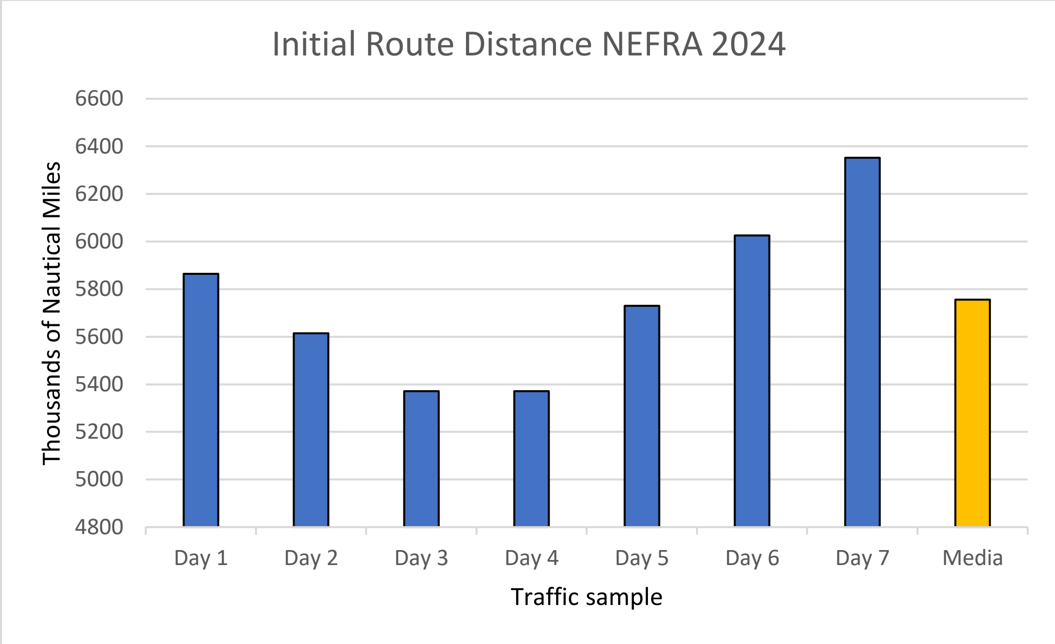

Figure 4.10 Initial distance of flights from NEFRA 2024

Figure 4.11 illustrates the traffic characterisation concerning free-route distance, where the mean value equals approximately 5,8 million NM.

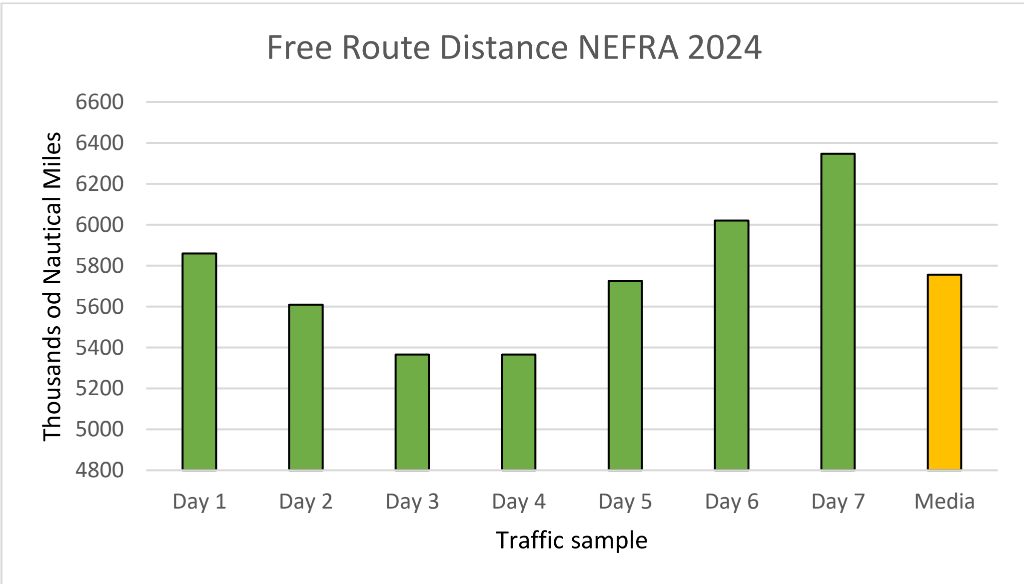

Figure 4.11 Free-route distance of flights from NEFRA 2024

As a general behaviour, the traffic sample patterns appear highly similar in initial and simulated traffic (see Figure 4.10 and Figure 4.11), presenting similar peaks in each pair of samples and days.

An explanation for this performance would be that this thesis uses traffic samples as loads for evaluating airspace structures and configurations. In this sense, changes in traffic samples must only represent indicators for evaluating airspace structure performance.

4.3.2. NEFRA Distance Saving Results

In general, findings further support the idea that the free-route implementation provides distance savings for airspace users.

Table 4.1 presents the values relating to NEFRA simulation. The differences between free-route and initial trajectories can be interpreted as the effects on route extension for airspace users. However, the observed difference between 2012–2018 and 2024 in this study was not significant regarding relative differences, as presented in Table 4.1.

Table 4.1 NEFRA distance savings

Measure	2012	2018	2024
Initial route distance (NM)	3416855,7	4480479,6	5761229,7
Free-route distance (NM)	3412539,4	4476850,4	5755947,1
Distance saving (NM)	4316,2	3629,2	5282,5

Another important finding concerns the smaller values for distance savings, which may be explained by the fact that the NEFRA structure began as a joined group of the following ACCs: EFIN (Finland), ESAA (Sweden), EKDK (Denmark), EETT (Estonia) and EVRR (Latvia). This could have resulted in optimised coordination between flights even before NEFRA implementation in 2012.

Adding to this, the NEFRA airspace file downloaded from Eurocontrol (Eurocontrol, Demand Data Repository, 2019) was found to be highly rigid in airspace structure, possessing few entry/exit waypoints. This would limit users' preferred trajectories, as explained in section 4.3.1 (scenario).

The next graphic (see Figure 4.12) illustrates the general values for distance savings, where it is easy to note that an approximately value of distance savings per day in NEFRA ranges between 3,6 and 5,3 thousand NM.

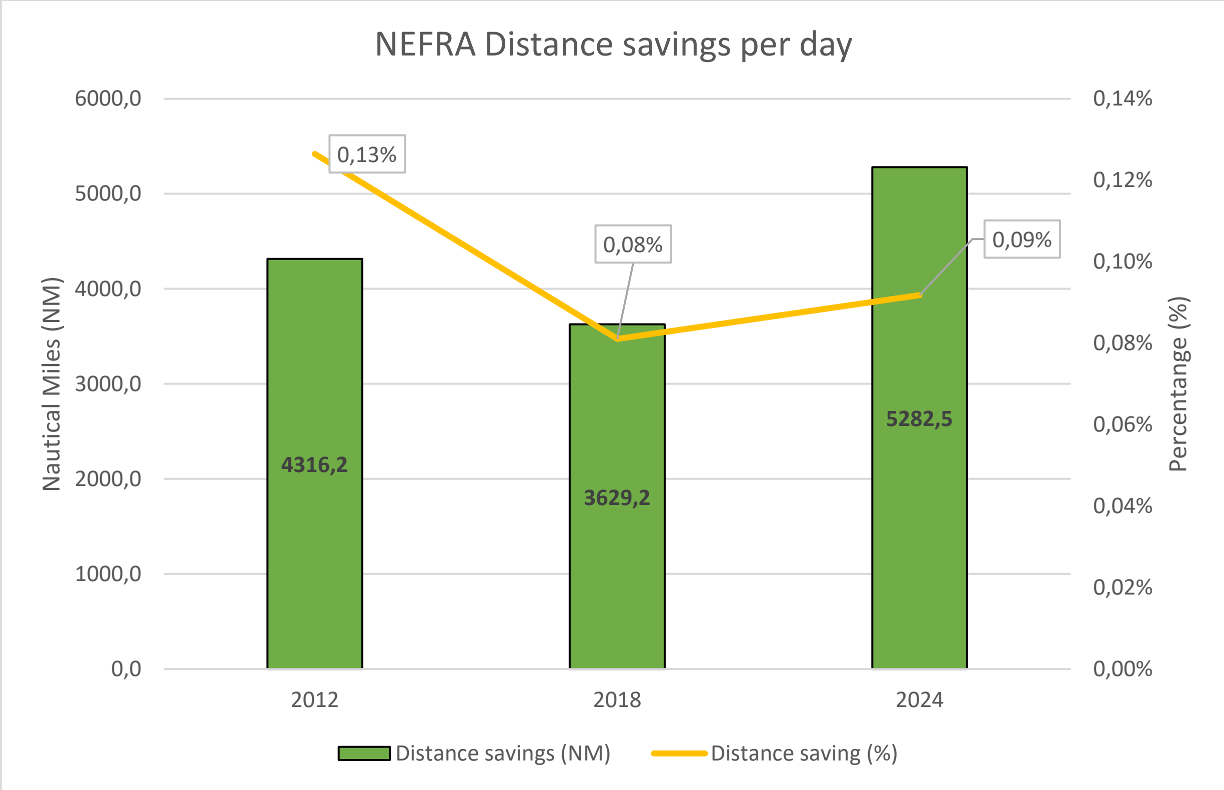

Figure 4.12 NEFRA Distance savings per day

In accordance with previous studies, these results have demonstrated that free-route implementation notably reduces flight distances, as maintained in this scenario.

As illustrated in Table 4.1, 2018 and 2014 featured more flights than 2012 and exhibited more gains for airspace users, all correlating to the number of flights per NM of distance saving.

4.3.3. NEFRA Flight Time Savings Results

Results for flight time in the NEFRA scenario resembles the savings in flight distance from 4.3.2. The next table (Table 4.2) summarises the main findings:

Table 4.2 NEFRA flight time savings

Measure	2012	2018	2024
Initial flight time (min)	7983,27	10243,90	13102,94
Free-route flight time (min)	7853,05	10155,94	12983,67
Flight time savings (h)	130,2	88,0	119,3

The flight time savings for 2018 and 2024 exceed those for 2012, achieving the lowest number of flights and demonstrating 30% more flight time savings as the traffic increases.

The next graphic (Figure 4.3) illustrates the main values related to flight time savings and confirms that free-route implementation is associated with flight time savings for airspace users.

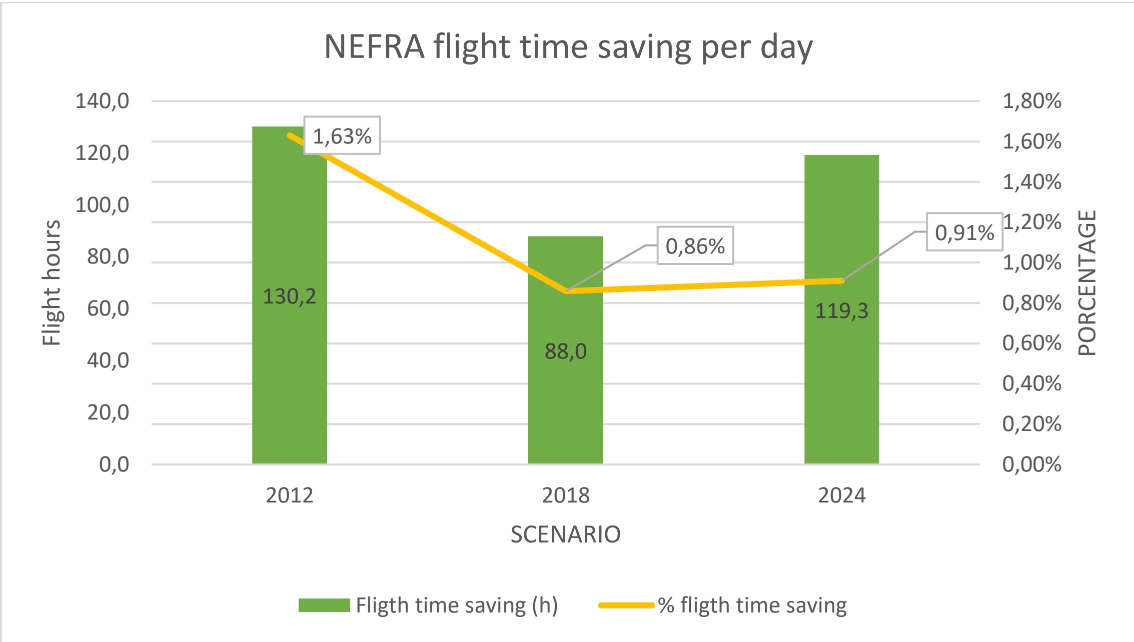

Figure 4.13 NEFRA flight time savings per day

The importance of flight time savings concerns the estimations of fuel consumptions and emission caused by engine running. These factors may explain the relatively positive correlation between values of flight time and fuel and emission extracted from Eurocontrol (Eurocontrol, NEST User Manual, Version 1.6, 2018), where the comparison thresholds are as follows:

- Time: 0,00823333 min
- Fuel: 0,275 kg
- CO_2: 0,8635kg
- NO_x: 0,0022kg

Applying those values to NEFRA flight time results, it is possible to estimate how much fuel, CO_2 and NO_x emissions can be saved with free route.

The next table (Table 4.3) presents the values per day resulting from this correlation:

Table 4.3 NEFRA fuel and emissions savings

Measure	2012	2018	2024
Flight time saving (h)	130,2	88,0	119,3
Fuel saving (tons)	261,0	176,3	239,0
CO2 emissions (tons)	819,5	553,5	750,6
NOx emissions (tons)	2,1	1,4	1,9

These results agree with the findings of other studies (ONATAP , 2011) in which free-route benefits are calculated and fuel and emissions are estimated based on the application of more direct routes.

Figure 4.14, demonstrates the simulated values and estimation according for the NEFRA scenario, describing the savings with free-route implementation and the three sets of traffic samples.

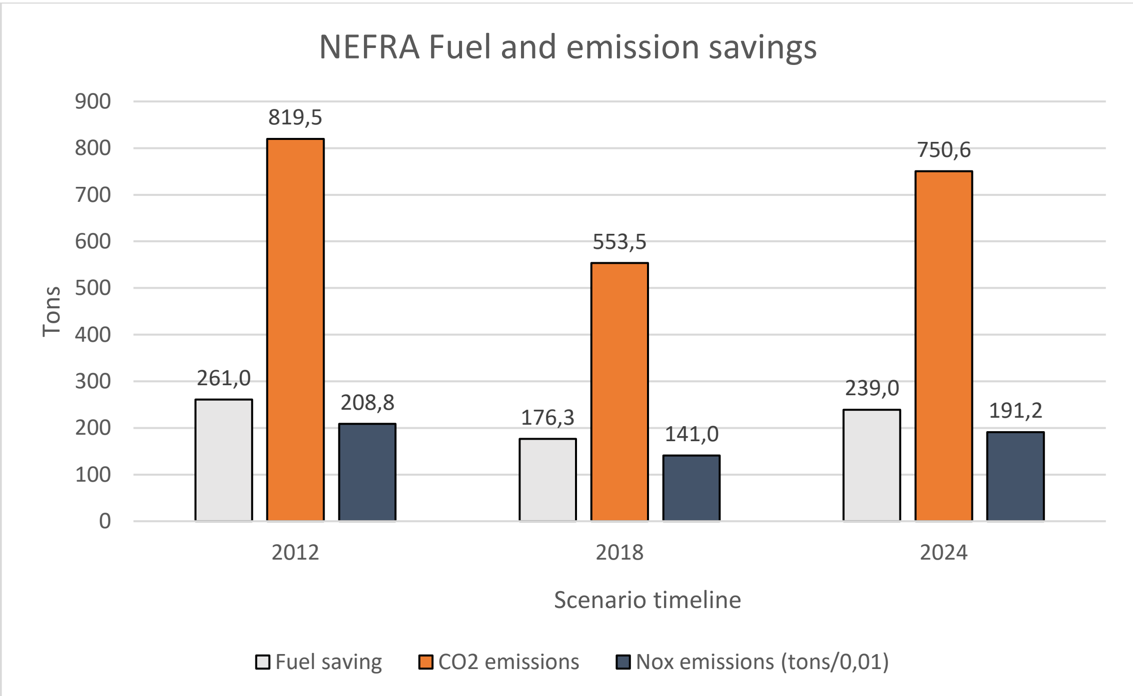

Figure 4.14 NEFRA fuel and emission savings per day

Figure 4.14 demonstrates that the estimate fuel savings per day in NEFRA reach approximately 176 to 239 tons, which can be translated into CO2 emission savings as 10 times the fuel values.

4.3.4. NEFRA Conflict Results

As mentioned in the literature review (2.6.2), the potential separation losses are defined as 'conflicts' and employed as indicators to determine how 'conflict' affects an airspace and traffic flow.

The main results involving potential conflicts are summarised in Figure 4.15, where it is evidenced that, as more traffic is applied to the evaluated scenarios, more conflicts are produced.

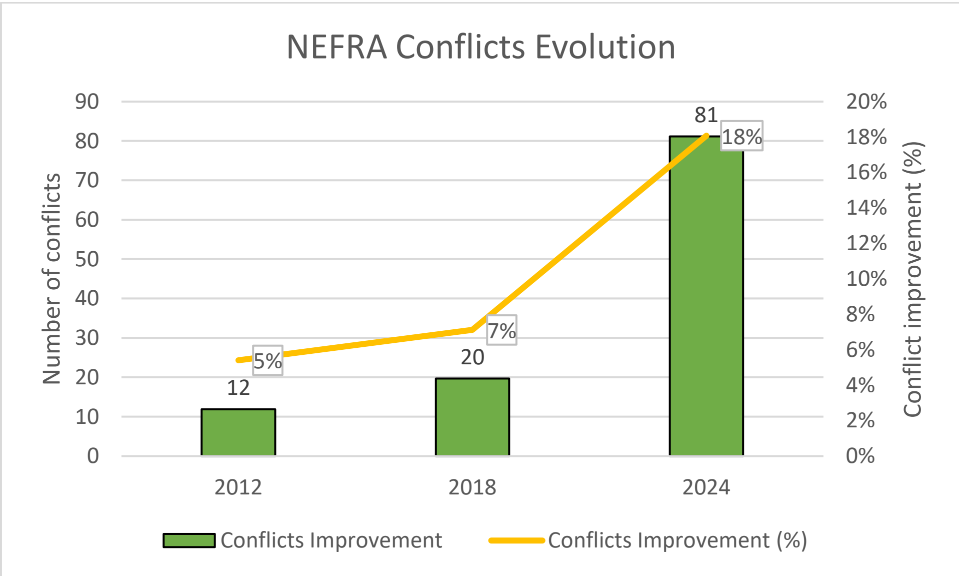

Figure 4.15 NEFRA conflict results

From Figure 4.15, it can be noted that, in all NEFRA scenarios, conflicts decrease with free-route implementation, shifting from 5% to 18% fewer conflicts in the initial scenario. A detailed study of conflicts is presented in the next figures, with Figure 4.19 separating conflicts by type.

4.3.4.1. Detailed conflict scenario NEFRA 2012

Concerning traffic from 2012, Figure 4.16 presents the results of conflicts for each day, indicating that the number of conflicts always remained less with free route (excepting day six) compared to previous scenario, in some cases reaching values approaching 14% less.

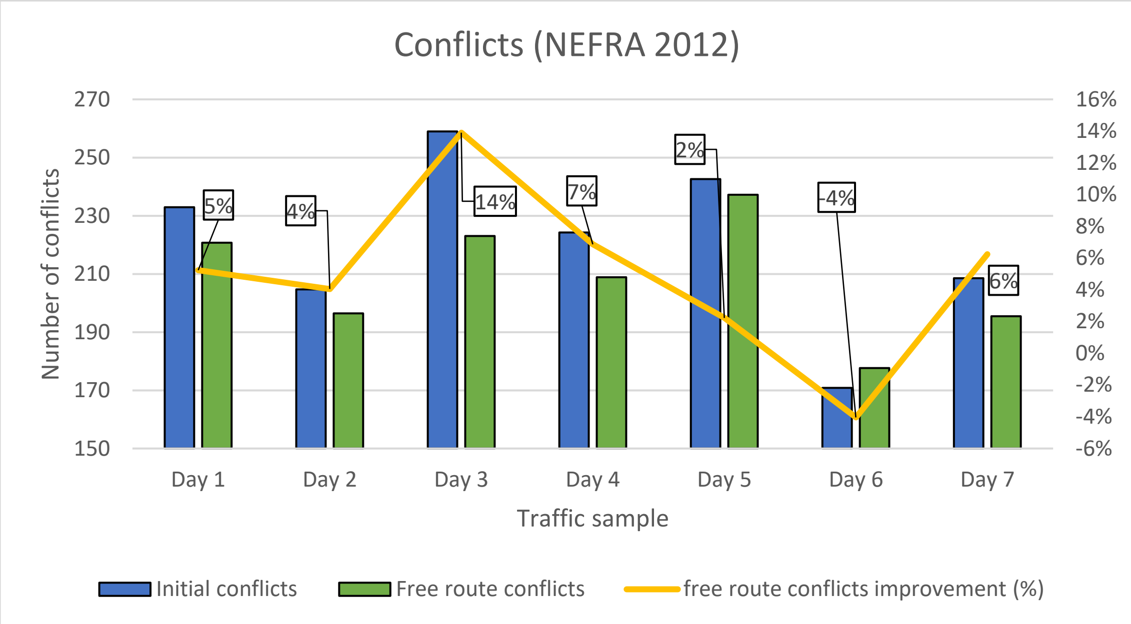

Figure 4.16 NEFRA total conflicts per day in 2012

For conflicts in the vertical dimension, simulations indicate that no constantly vertical conflicts are reduced with free route. The summarised results are presented in Figure 4.17:

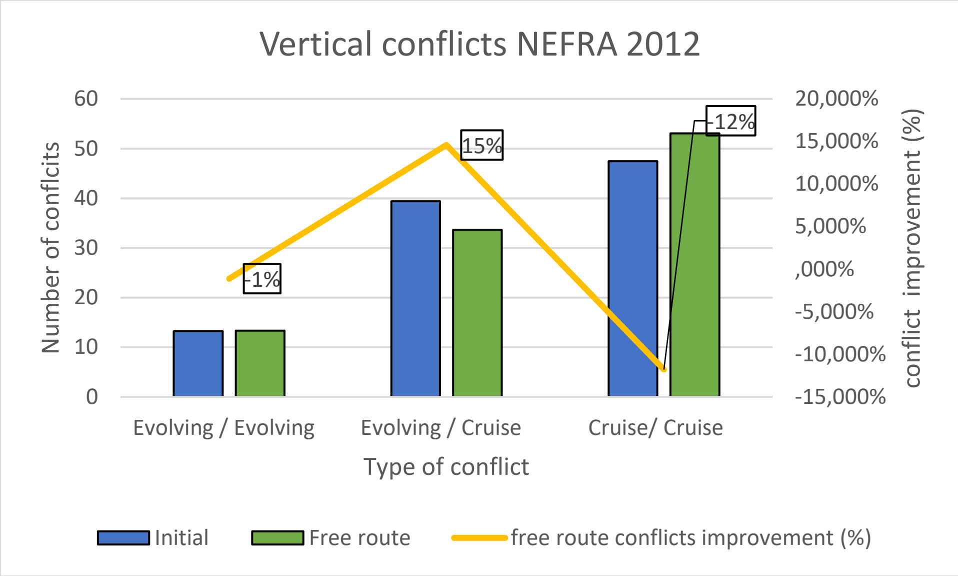

Figure 4.17 NEFRA vertical conflicts per day in 2012

The vertical conflict results relate to three different flight statuses:

- Flights in Evolving / Evolving
- Flights in Evolving / Cruise
- Flights in Cruise/ Cruise

The present results are significant in at least major two respects: fewer conflicts with traffic cruise/evolving, which means that traffic is more segregated in the same FL (flight levels), and consequently, more conflicts occur in cruise/cruise traffic.

For the horizontal dimension, results suggest that with free-route implementation, conflicts increase, specifically by 14% in crossing trajectories.

These results relate to the last exposed from vertical dimension, where cruise/cruise conflicts increased significantly by 12%.

Figure 4.18 condenses the horizontal conflicts with the traffic simulated from 2012:

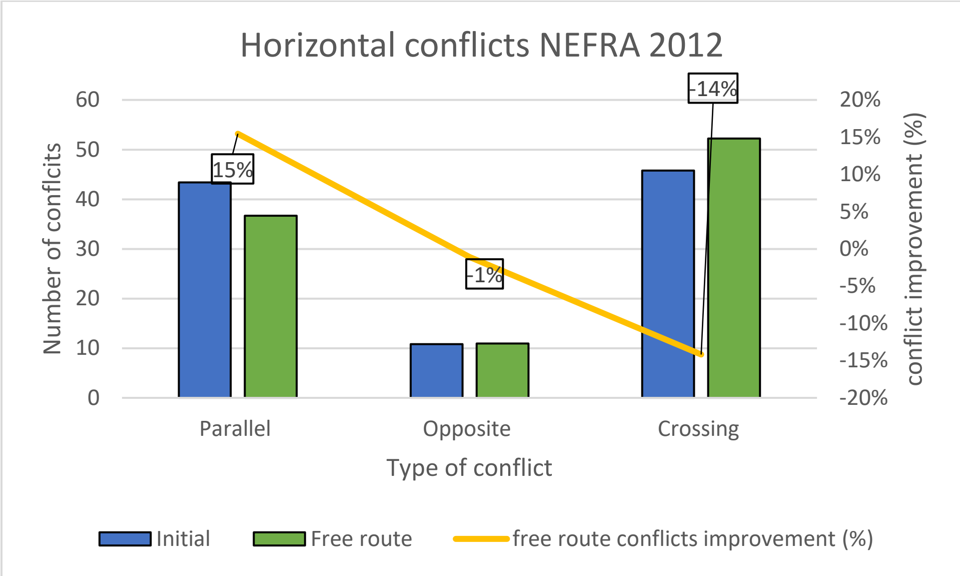

Figure 4.18 NEFRA horizontal conflicts per day in 2012

Regarding NEFRA traffic from 2012, Figure 4.19 summarises all conflict types and differences between the free-route scenario and the initial one (no free route). This combination of findings offers some support for the conceptual premise explained regarding the section of conflicts from 2012, where horizontal conflicts in particular increased with free route.

In line with the increase in horizontal dimension conflicts, the highest value is presented for cruise/cruise crossing trajectories, reaching an increase of 22% in conflicts with free route.

For the vertical dimension, the evolving status evidences significant reductions, as evidenced in evolving /cruise parallel trajectories, reaching 25% fewer conflicts.

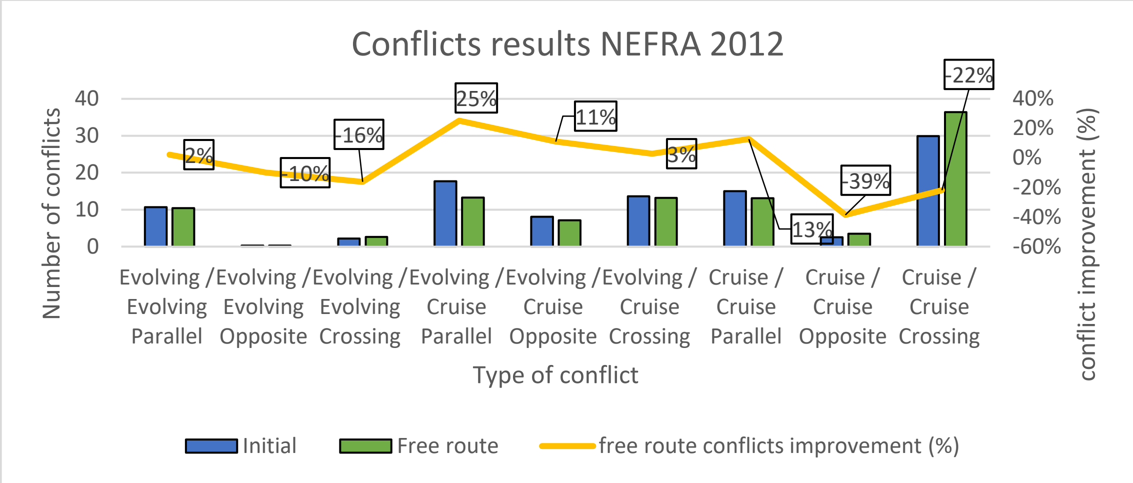

Figure 4.19 NEFRA conflict type results per day in 2012

4.3.4.2. Detailed conflict scenario NEFRA 2018

In the case of NEFRA simulations with traffic from 2018, the total number of conflicts per day are presented in Figure 4.20. Based on these findings, some immediately notable conclusions are worth discussing.

First, the total number of conflicts is reduced in the free-route scenario, with values reducing by 4 to 11% compared to the initial evaluated traffic.

Second, the increase in the number of flights is evidenced through the increase in the total number of conflicts. With 500 more flights than 2012, conflicts increase numerically by approximately 80 (see Figure 4.20).

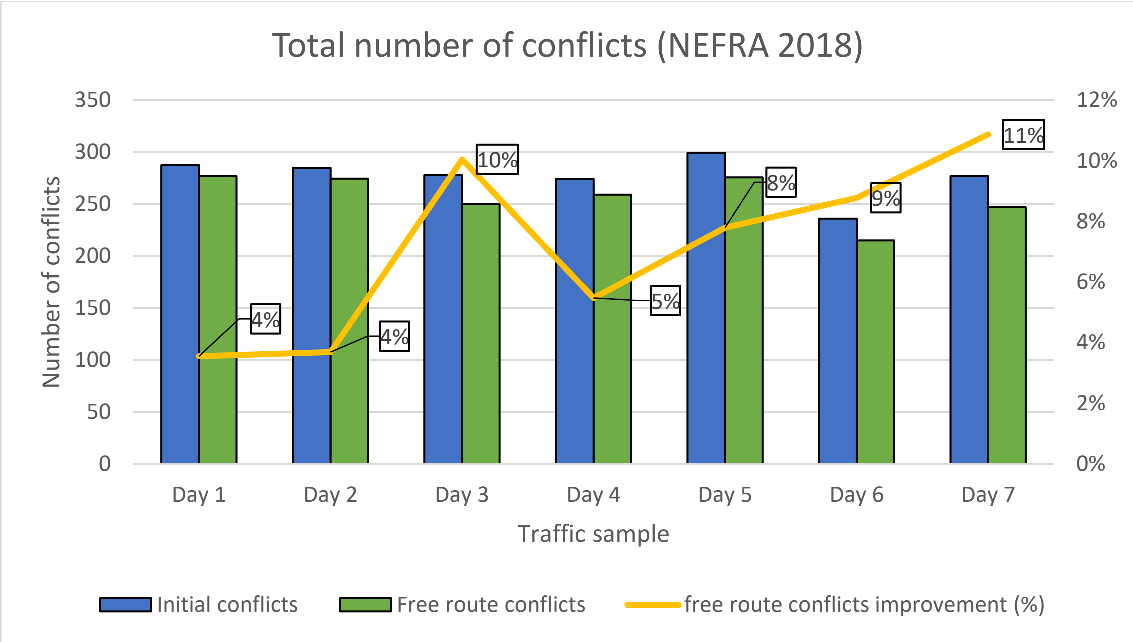

Figure 4.20 NEFRA total number of conflicts per day in 2018

The study of vertical conflicts with NEFRA traffic from 2018 is represented in Figure 4.21. The data indicates patterns similar to traffic from 2012, where conflicts in cruise/cruise trajectories are increased.

In the case of NEFRA 2018, cruise/cruise conflicts increase by approximately 13% while, conversely, evolving/cruise decreases by 14% compared to the initial scenario.

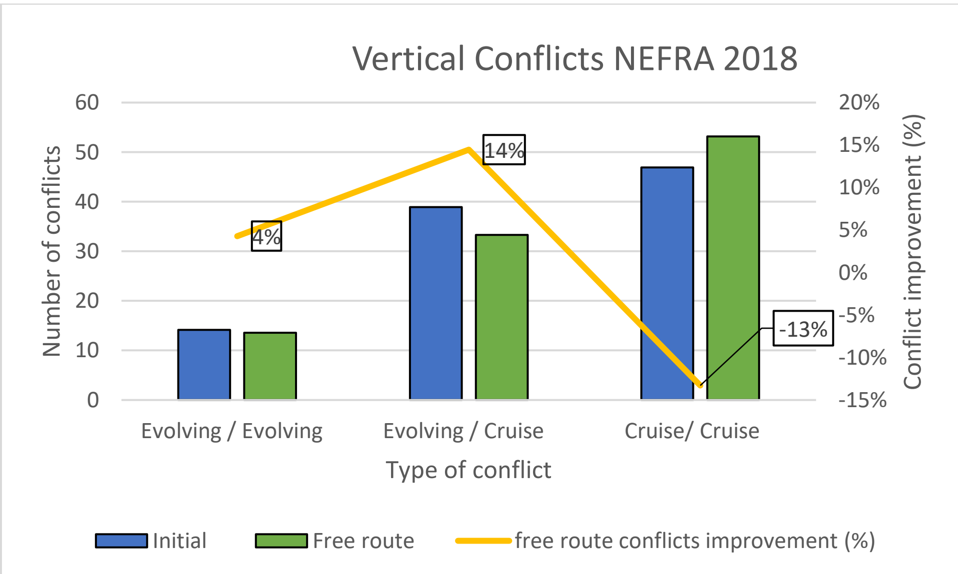

Figure 4.21 NEFRA vertical conflicts per day in 2018

In the horizontal dimension (see Figure 4.22), crossing conflicts produced the most remarkable result with an increase of 11%. These results further support the hypothesis that, in FRA, users flying preferred trajectories randomly increase the flows, stratifying the flight levels as a result of this freedom.

All these results are compared with the complexity values (4.3.5) to conclude whether horizontal conflicts maintain correlation with horizontal interactions and structural index.

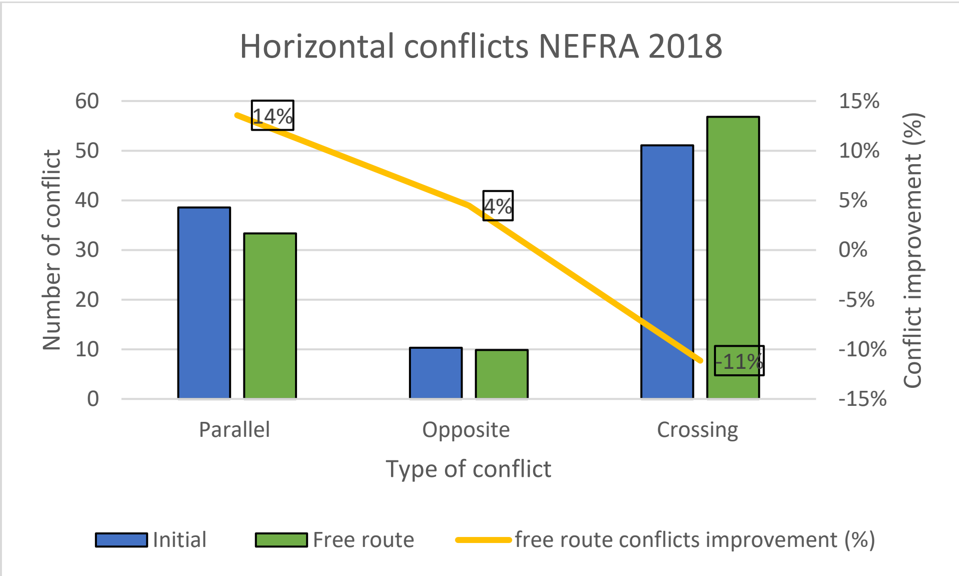

Figure 4.22 NEFRA horizontal conflicts per day in 2018

A general overview of the conflict type in NEFRA 2018 is presented in Figure 4.23. These findings suggest patterns similar to the previously analysed traffic. For instance, cruise/cruise conflicts increased, indicating horizontal changes in traffic flows derived from free route. On the other hand, the evolving trajectories crossing with cruise decreased under the free-route scenario.

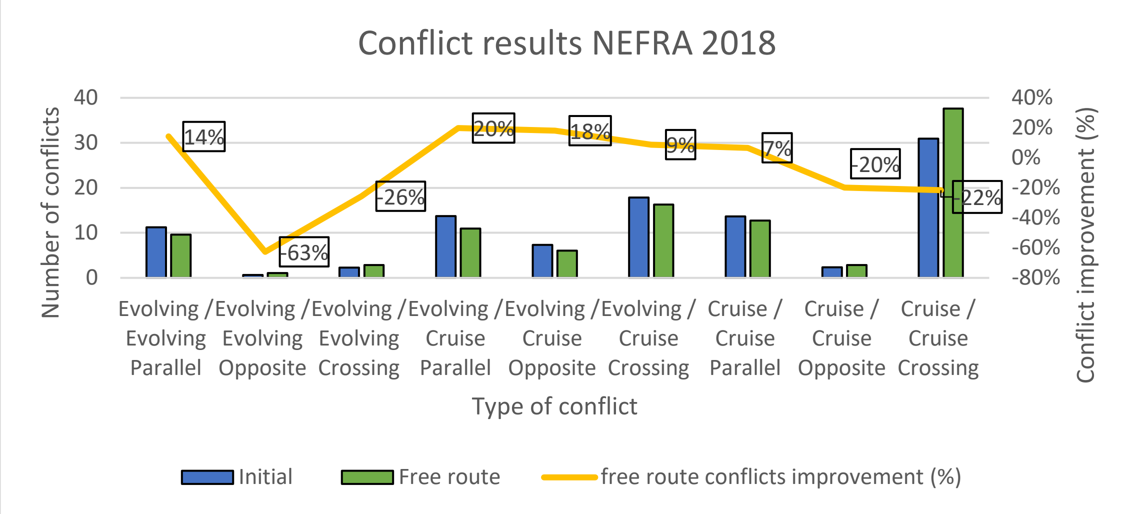

Figure 4.23 NEFRA conflict type results per day in 2018

4.3.4.3. Detailed conflict scenario NEFRA 2024

For simulations of NEFRA 2024, the present findings (Figure 4.24) appear consistent with the other results presented in this section, demonstrating a clear decrease in the percentage of conflicts compared to free route, achieving values between 14 to 22% against the initial prognosis.

Figure 4.24 illustrates the total number of conflicts per day for traffic data from 2024.

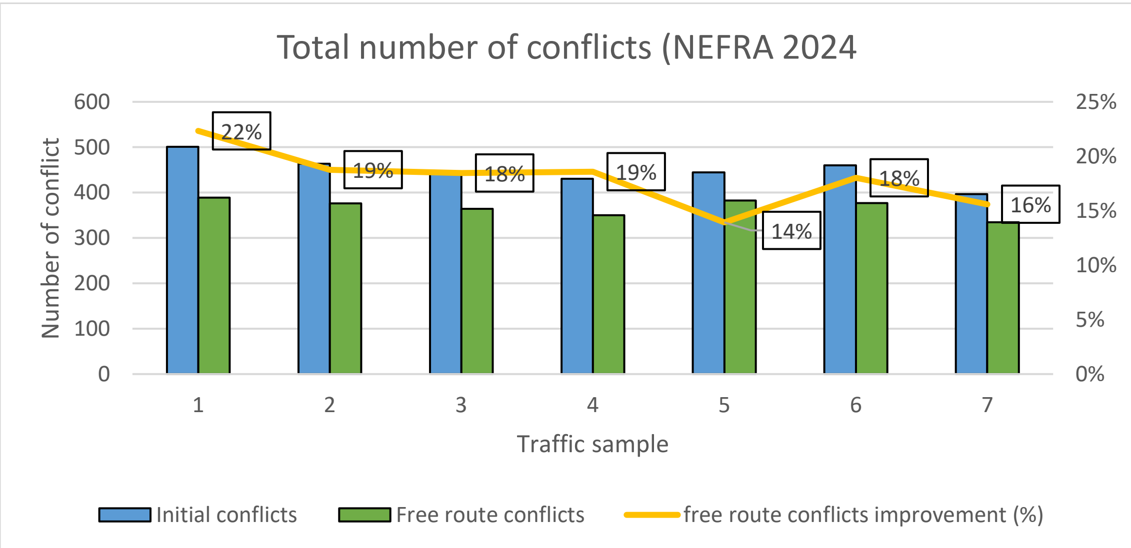

Figure 4.24 NEFRA total conflicts per day in 2024

Concerning the vertical dimensions (see Figure 4.25), results from NEFRA 2024 exhibit similar behaviour, demonstrating approximately 13% increases in the number of cruise/cruise conflicts and a remarkable decrease in evolving/cruise conflicts by 14%.

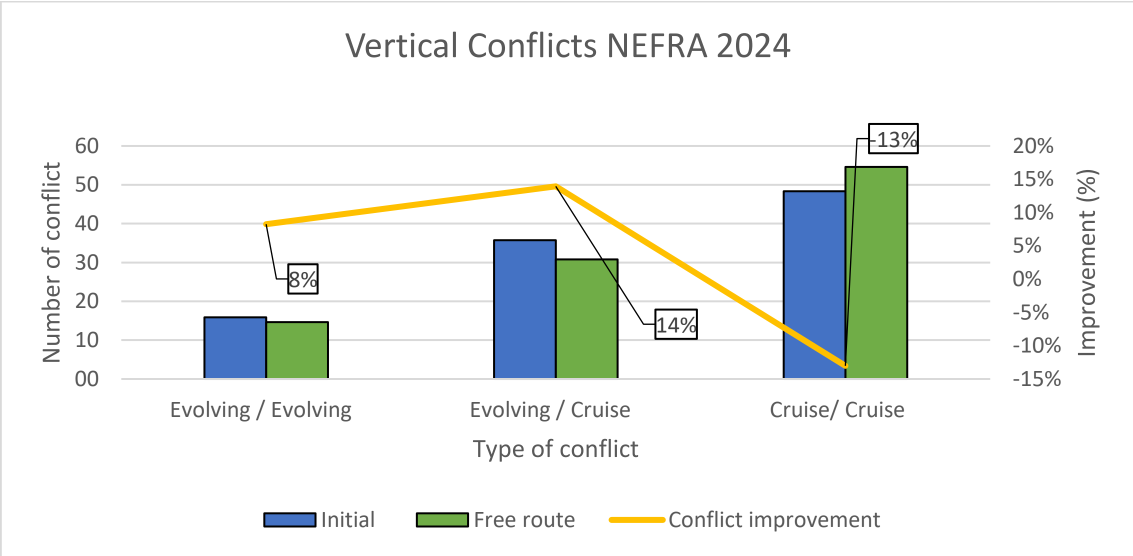

Figure 4.25 NEFRA vertical conflicts per day in 2024

Figure 4.26 depicts the horizontal conflicts from the 2024 traffic. Here, differences remain in the increase in horizontal crossing according to the simulations. The opposite and parallel trajectories present decreasing values, as previous graphics described in the NEFRA section.

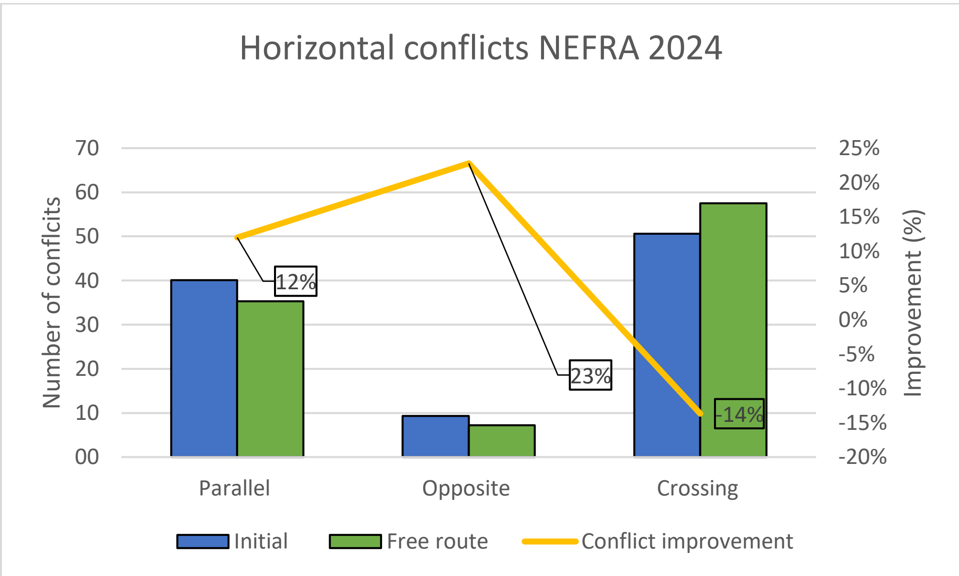

Figure 4.26 NEFRA horizontal conflicts per day in 2024

Finally, the overall conflict type from NEFRA 2024 is presented in Figure 4.27. From this figure, it is notable that cruise/cruise crossing traffic experiences the highest peak with 22% more conflicts compared to the no-free-route scenario.

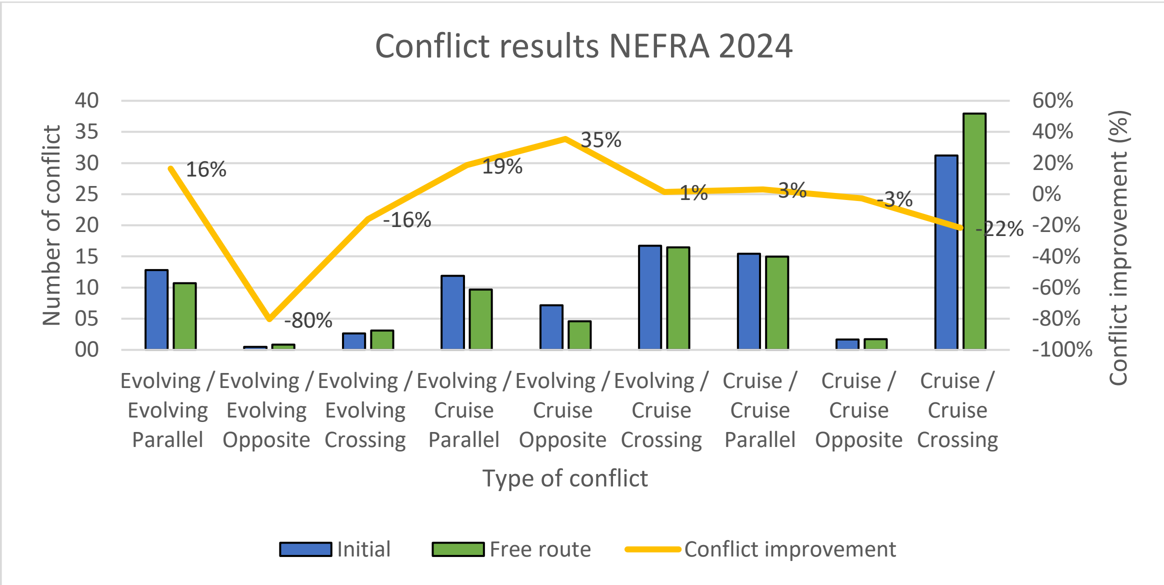

Figure 4.27 NEFRA conflict type results per day in 2024

4.3.5. NEFRA Complexity Results

The complexity section provides additional evidence concerning free-route implementation in NEFRA. Specifically, analysing the complexity indicators demonstrates whether free route makes the airspace structure more complex or ‘difficult to manage’.

4.3.5.1. NEFRA Adjusted density

The main relation between interactions and traffic involves adjusted density. The next figure presents the adjusted density in the NEFRA scenario with all traffic samples:

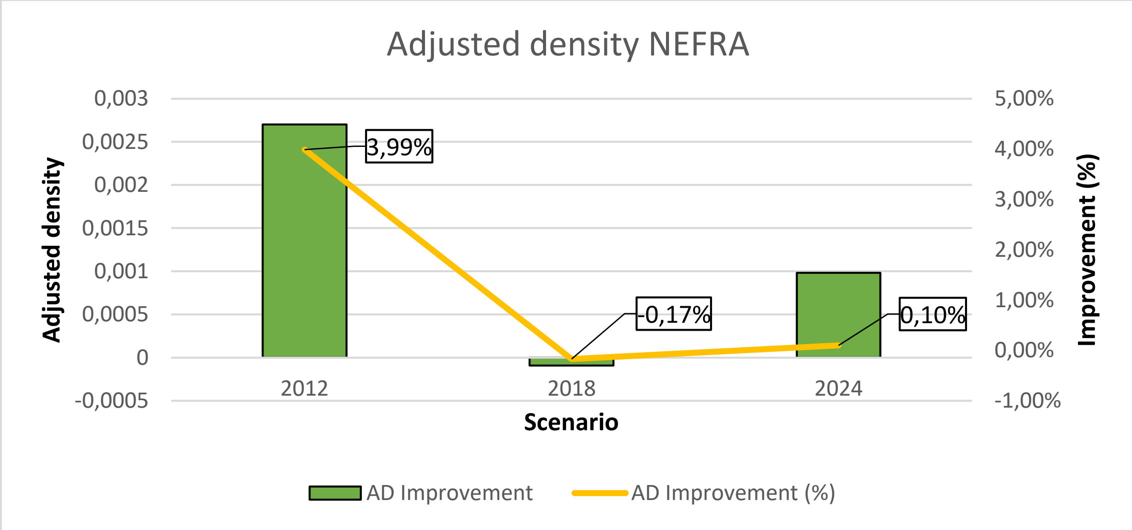

Figure 4.28 NEFRA total adjusted density per day

As illustrated in Figure 4.28, the adjusted density difference generally decreases with free-route implementation, with the ratio of interactions per flight-controlled hours increasing under free route. This represents an expected result for the free-route simulation with three different traffic load volumes.

The different traffic values from 2012 to 2024 suggests that at least the adjusted density will be affected by the increase in controlled flight hours, as this changes from 2800 in 2012 to approximately 3900 flights in 2024 (see Figure 4.9).

Conversely, this general result of decreases in adjusted density values indicates changes in complexity with free-route implementation. A detailed study of interactions in NEFRA is accordingly presented in the followed figures throughout this section.

Regarding values of adjusted density in 2012, these increase with free-route implementation, as presented in Figure 4.29. These results support the increase in interactions with FRA, resulting in the highest values of adjusted density even with the increase in controlled flight hours.

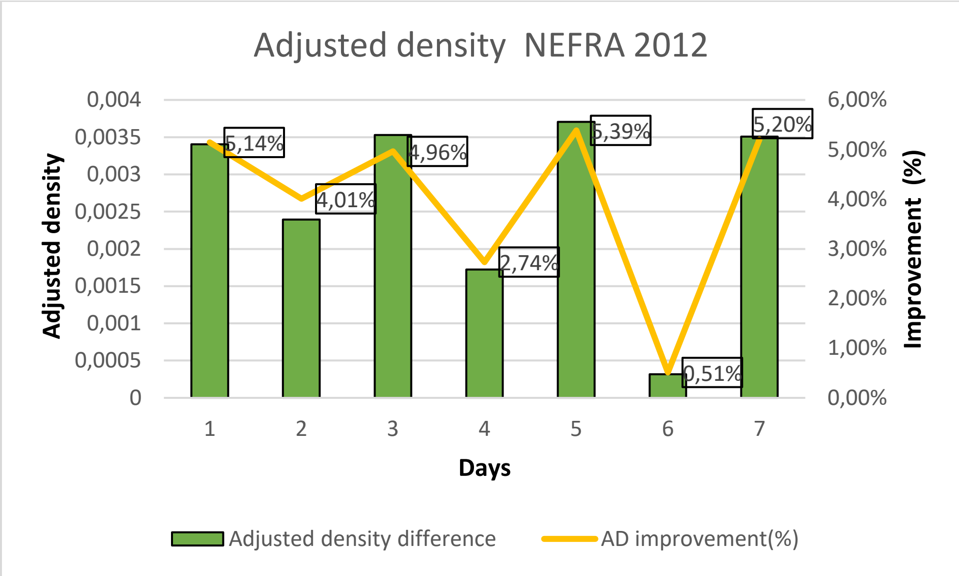

Figure 4.29 NEFRA adjusted density per day in 2012

For 2018 adjusted density results, the values presented in Figure 4.30 reveal that the increase in traffic will generate a less favourable result for free route. This is clearly supported by the number of flights producing an increase in the number of interactions, resulting in lower values of adjusted density for free route, as illustrated in Figure 4.30 through the difference of adjusted density.

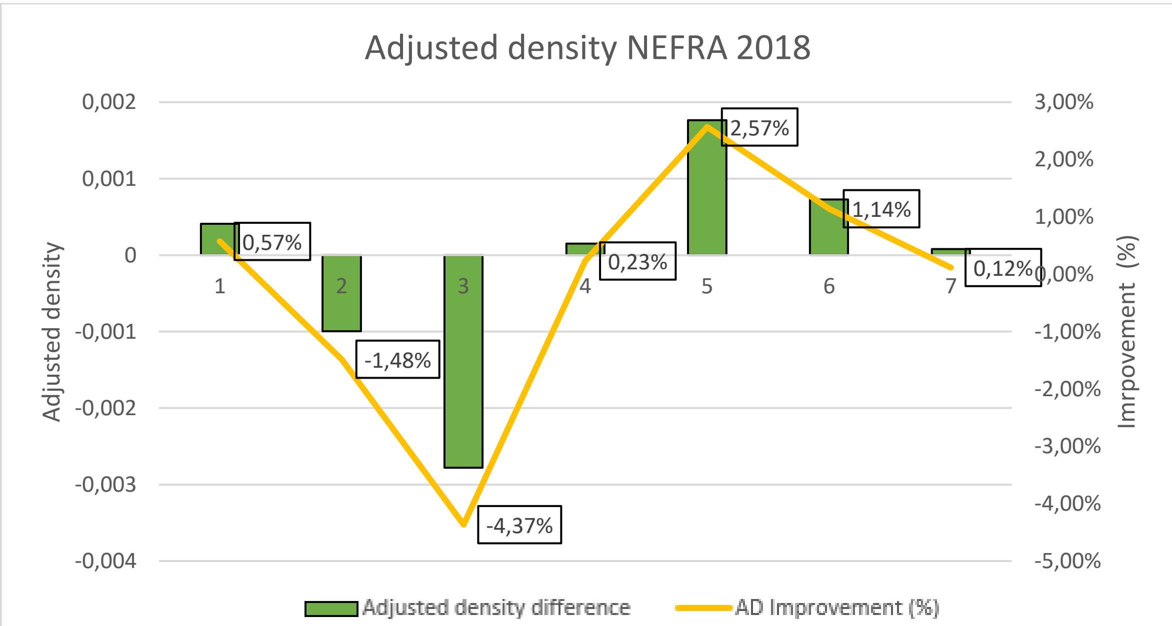

Figure 4.30 NEFRA adjusted density per day in 2018

Similar results for the 2024 traffics are presented in Figure 4.31, where reduced values of adjusted density differences are related to the increase in interactions in the area of study.

For the 2024 samples, the values indicate that free route improves adjusted density values and in only one case marginally increases the adjusted density in NEFRA (see Figure 4.31).

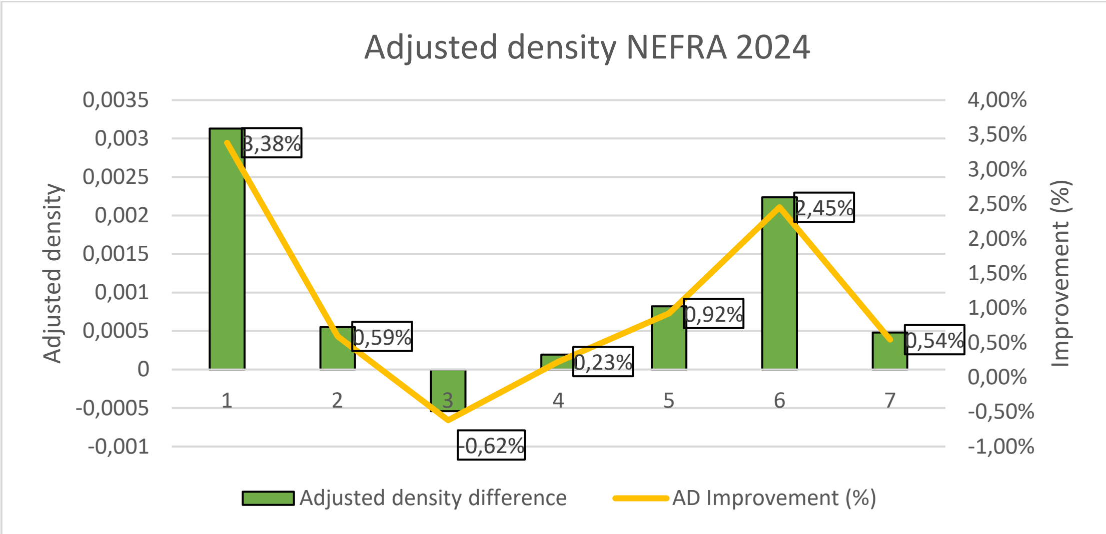

Figure 4.31 NEFRA adjusted density per day in 2024

4.3.5.2. NEFRA Complexity indicators

The study of the vertical interactions, described in Figure 4.32, supports the findings related to vertical conflicts, demonstrating that, with free-route implementation, interactions in the vertical dimension are reduced by approximately 18–24% compared to the base scenario.

Figure 4.32 describes the results for the vertical indicator related to NEFRA simulations:

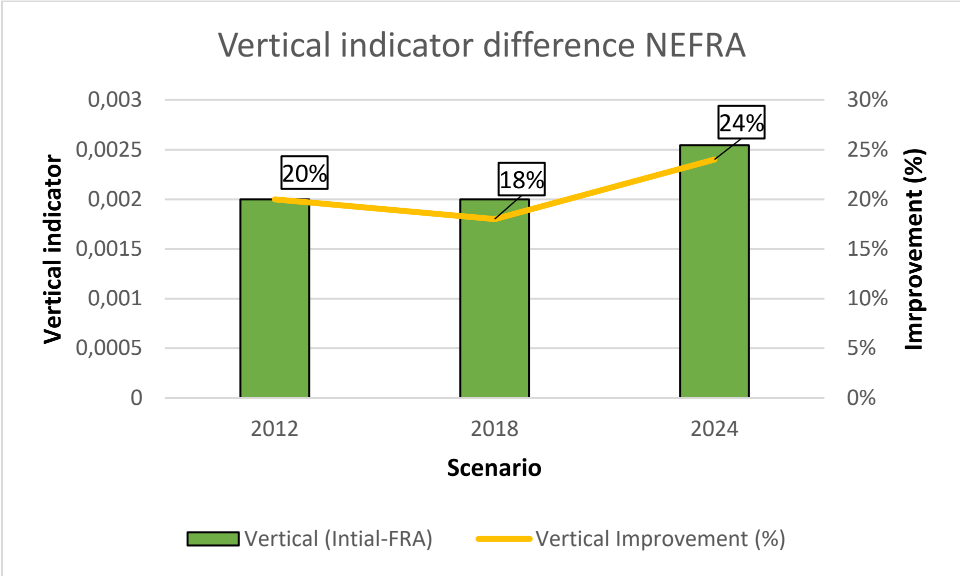

Figure 4.32 NEFRA vertical indicator

Nonetheless, the horizontal indicator (see Figure 4.33) indicates that free route increases interactions in this dimension by 6–8%. This result relates to the increase in crossing trajectories, as previously presented in horizontal conflicts.

As the main change with free route concerns the implementation of preferred routes by airspace users, this produces random and unexpected interactions, primarily detected in the horizontal flows according to the demonstrated results.

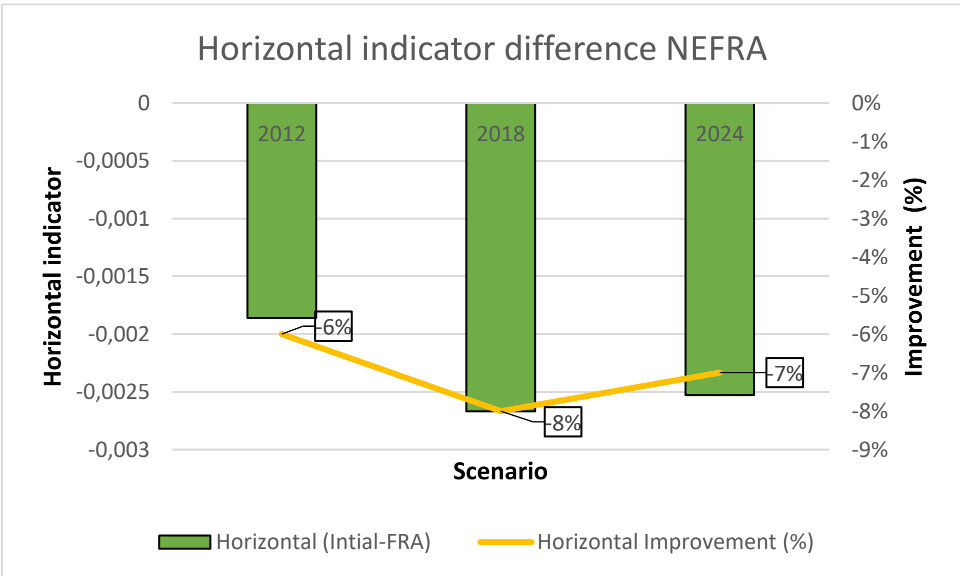

Figure 4.33 NEFRA horizontal indicator

The third indicator, the speed indicator, relates to traffic mixes (see Figure 4.34). For this measure, results indicate that free route drastically enhances the traffic mix interactions. In other words, this means better distribution or segregation of aircraft according to their speed, reducing interactions and complexity.

Regarding the speed indicator, Figure 4.34 compares the highest load traffic from 2024, which reach approximately 54% fewer vertical interactions under free route compared to the initial scenario with a fixed airway network.

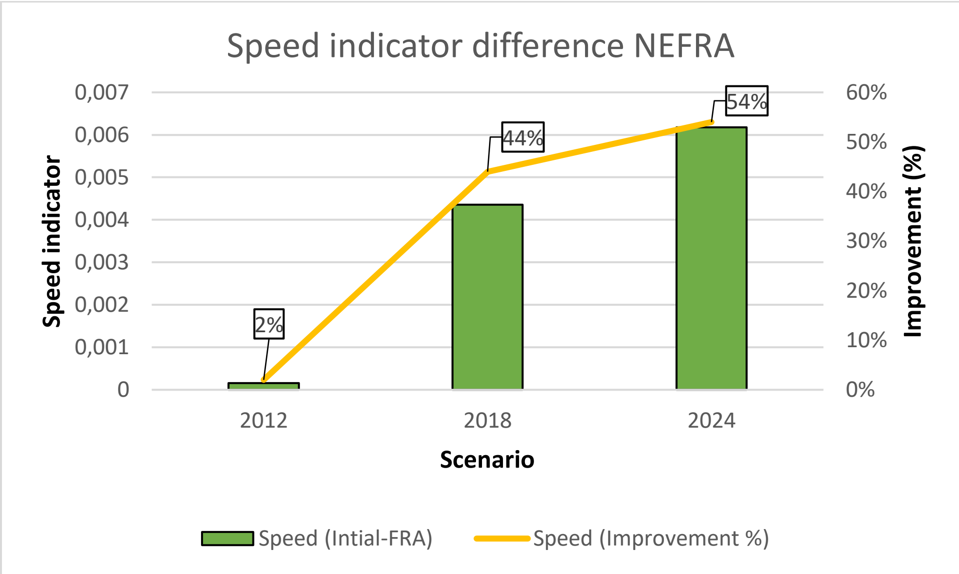

Figure 4.34 NEFRA speed indicator

4.3.5.3. NEFRA Structural Index and Complexity Score

The results for NEFRA complexity are synthesised into two main indicators: structural index and complexity score, both defined in chapter three.

From the structural index analysis, it can be said that free-route implementation in NEFRA improves results by reducing the global number of interactions, thus reducing complexity.

Figure 4.35 summarises the structural index results, demonstrating that, as traffic interactions related to structural index decrease, this results in increases close to 10% compared to 2024 traffics.

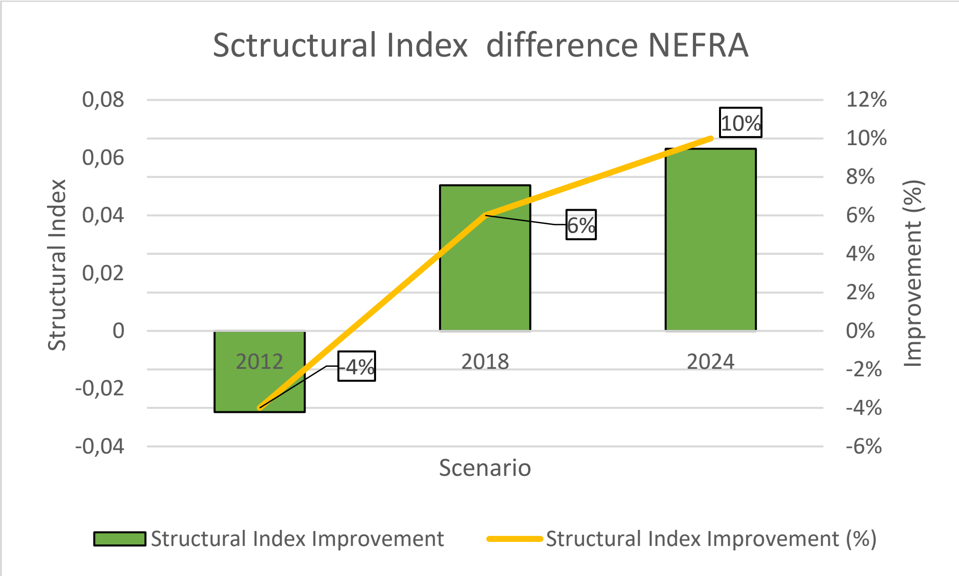

Figure 4.35 NEFRA structural index

The results for the complexity study produce the complexity score, which is based on the structural index values, but with independency of the flight-controlled hours. As such, this score indicates the global complexity of the studied airspace condensed in value.

As the complexity score correlates with the structural index, the results are highly similar, presenting increases in complexity under free route with a favourable tendency as the traffic increases (see Figure 4.36).

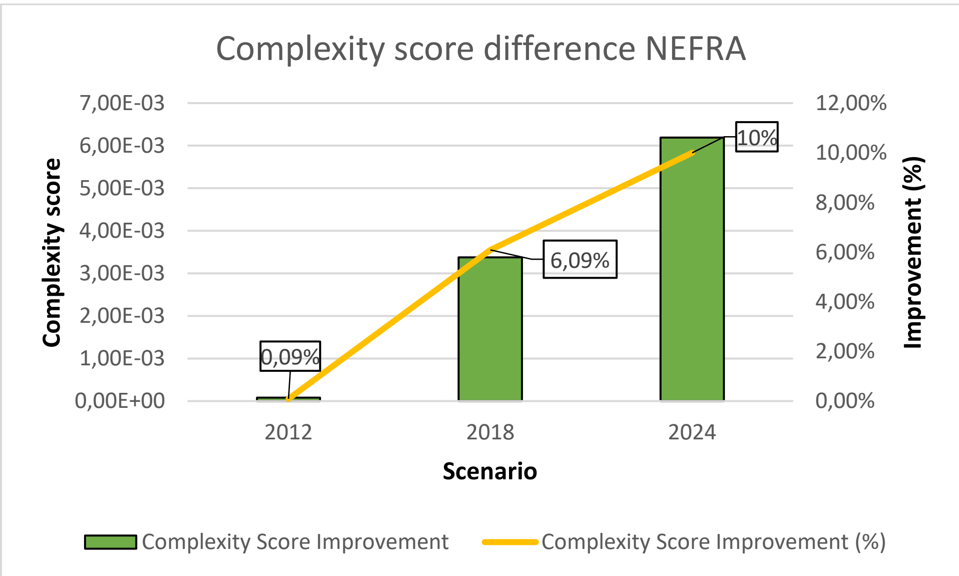

Figure 4.36 NEFRA complexity score

As the main result, free-route implementation in NEFRA area produces important reductions in global complexity. Nonetheless, increases in horizontal crossing interactions occur that were compensated with a reduction in vertical and speed interactions.

The detailed values related to NEFRA simulations are described in APPENDIX A – Detailed Results.

5. Southwest FAB Airspace

Structured much like the previous chapter, this section presents the simulation results related to the Southwest FAB airspace.

The SW FAB features one notable difference compared to the previous scenario, it involves an enormous area to evaluate, as the SW FAB includes the Atlantic Oceanic airspace.

The chapter is structured as follows:

- Traffic characterisation (traffic samples)
- Route length and distance saving analysis
- Flight time and emission calculations
- Traffic conflicts
- Complexity study

5.1. Scenario

The initial scenario used for SW FAB simulations is based on the ATS network from October 2018.

Here, the FRA area is not fully implemented, as Lisbon ACC and Santa Maria Oceanic function separately, while the Spanish free-route FRASAI it remains separated from Lisbon ACC.

However, the free-route scenario was based on the Final Phase III from the literature corresponding to Southwest FAB development (SW FAB , 2019).

Figure 5.1 illustrates the area under study in this chapter, which concerns Lisbon, FRASAI and Santa Maria Oceanic without borders as unique airspace blocks.

Figure 5.1 SW FAB extension

As presented in Figure 5.1, the area under study involves approximately 2200 NM and forms the main corridor between Europe and Central and South America. The waypoints configuration employed in the initial scenario correspond with the free-route waypoints already used in Lisbon and FRASAI, as well as the Oceanic waypoints utilised by the current airspace in 2018.

Meanwhile, the network configuration for the full free-route scenario from Phase III possesses approximately 260 free-route waypoints; from these, roughly 105 correspond to E, X or E/X waypoints, while the rest are intermediates.

For Oceanic airspace, many of the waypoints are separated by 10 degrees, and certain zones feature only a few waypoints supporting the network.

The vertical limits, as for NEFRA, range from FL 245 to 660.

5.2. SW FAB Evaluation

The SW FAB evaluation is oriented to compare two scenarios. Using the October 2018 scenario as the basis, the futuristic free-route scenario considers one of the final phases of free-route implementation between Spain and Portugal (SW FAB).

Exploring these low-traffic load scenarios with the highest free-route area, it will be possible to identify free-route behaviour in airspace corridors.

Figure 5.2 illustrates the main traffic flows identified in SW FAB.

Figure 5.2 SW FAB main traffic flows (SW FAB , 2019)

From Figure 5.2, it is easy to see that the main flows are focussed on traffic coming through Lisbon ACC and Spain, without any notable flow in the middle of Santa Maria Oceanic. Here, it is important to note that the main Atlantic traffic flows involve Shanwick and Gander airspace; the SW FAB's only impacts from South American flights come through Canary Islands ACC.

5.2.1. SW FAB Results

Results from the SW FAB are summarised in figures and graphics as in the previous chapter, though it is important to note the following aspects:

- Green bars and lines correspond to the difference between free route and initial values or not free route.
- Blue bars correspond to initial values.
- Orange bars and lines relate to the mean of presented values.
- For simplicity, a difference between free route and initial traffic is presented in percentage (%).

5.2.2. SW FAB Traffic Characterisation

The lowest traffic load considered for the SW FAB study relates to 2012. As described in Figure 5.3, the mean traffic equals approximately 1460 flights, with a notable traffic sample peak of 1517 on day six, only 4% higher than the mean.

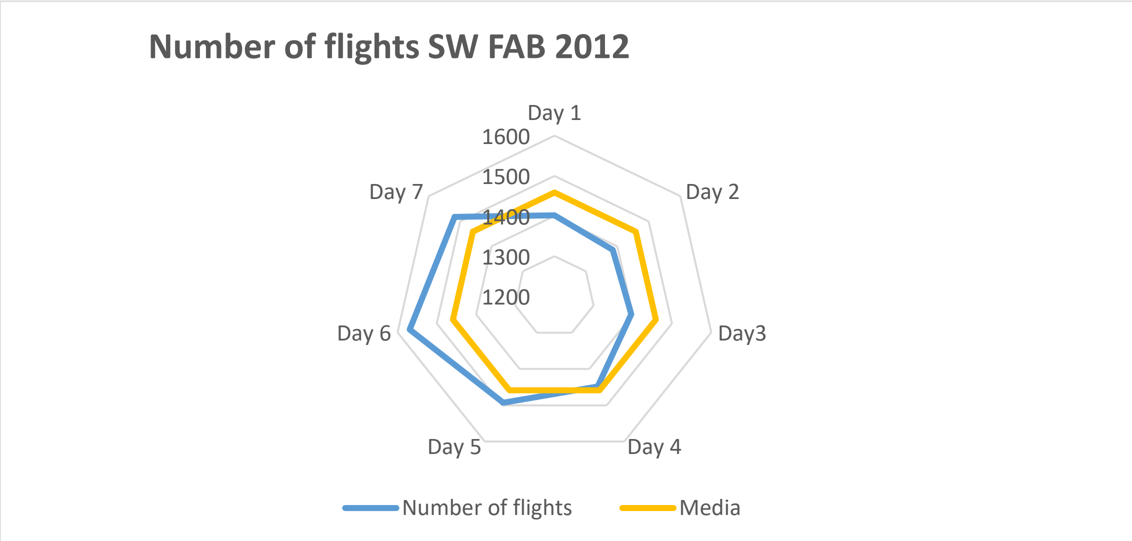

Figure 5.3 SW FAB number of flights in 2012

Relating the last traffic with the route length, Figure 5.4 represents the total flight distance and mean used for the comparative study with free-route samples.

From here, it is easy to note that the approximate flight distance in the initial traffic sample from 2012 corresponds to 2.47 M NM.

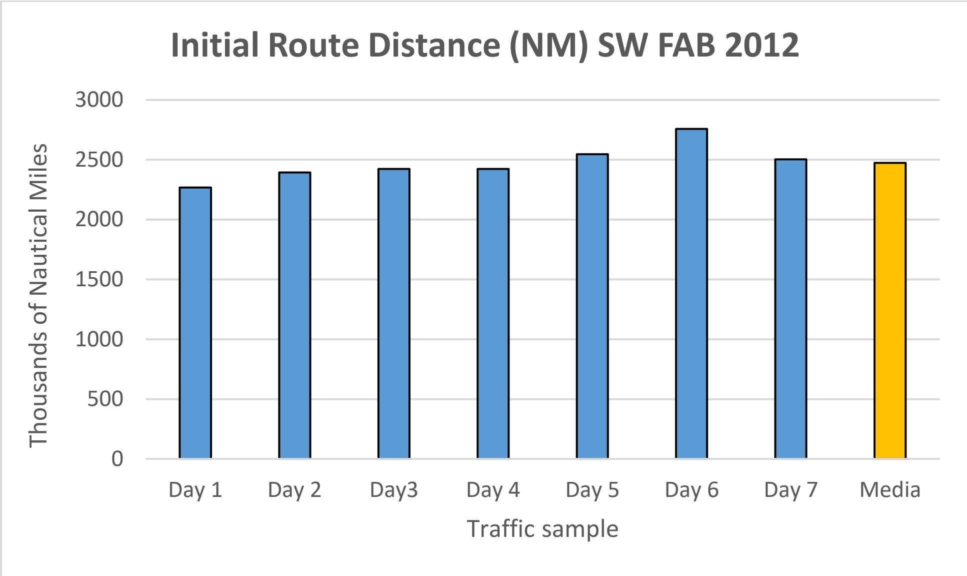

Figure 5.4 SW FAB initial route distance in 2012

Then, demonstrating a number of similarities to the previous figure (see Figure 5.4 and Figure 5.5), the free-route distance media for 2012 exhibits a decrease in distance flown by around 2.46 million of NM, as evaluated in the following sections.

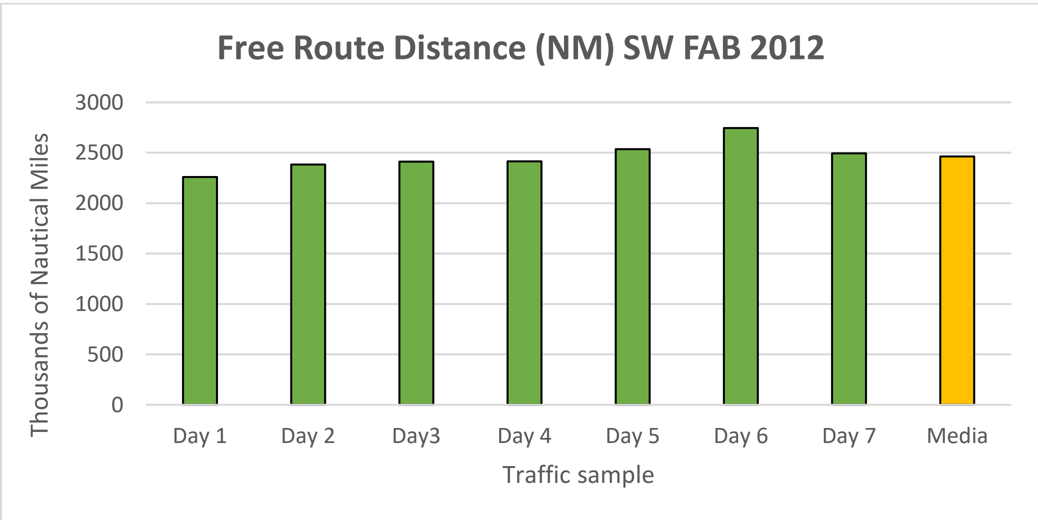

Figure 5.5 SW FAB free-route distance in 2012

The distribution represented in Figure 5.6 concerning the traffic sample from 2018 exhibits dispersion, with a mean of 2076 flights. In this sense, deviations from day five and seven equal approximately 3–5% of the total compared to the mean. The following graphic illustrates the traffic sample from 2018 used in the SW FAB scenario.

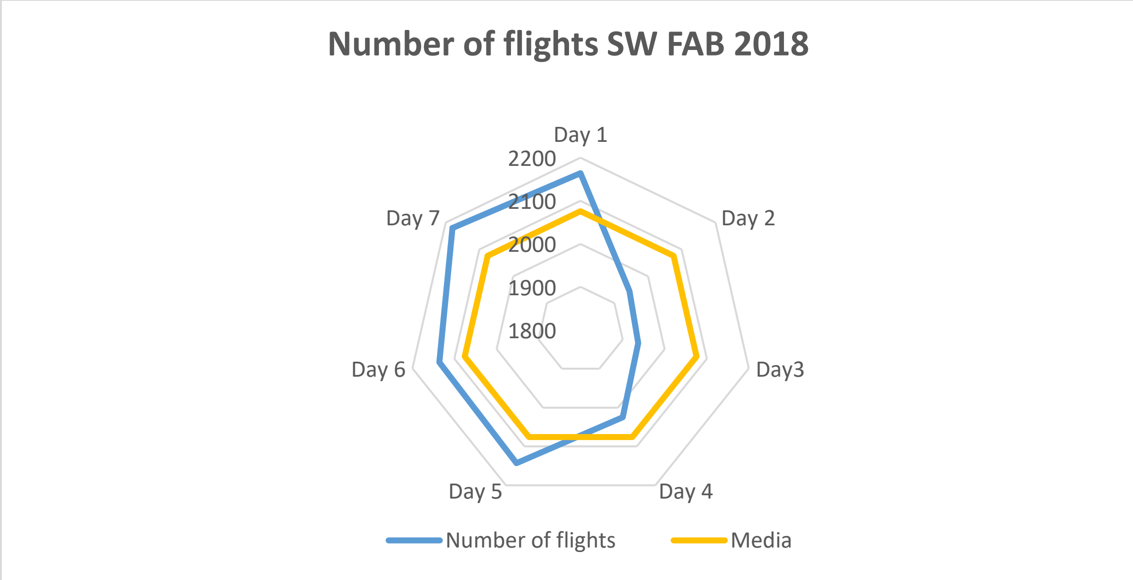

Figure 5.6 SW FAB number of flights in 2018

Compared to the number of flights from Figure 5.6, an increase of 600 flights can be noted in 2018. Regarding the 2076 flights from 2018, the distance flown approximated 3,46 M NM, as presented in Figure 5.7.

The lowest distance values from days two and three correspond to 9–10% deviations from the demonstrated mean.

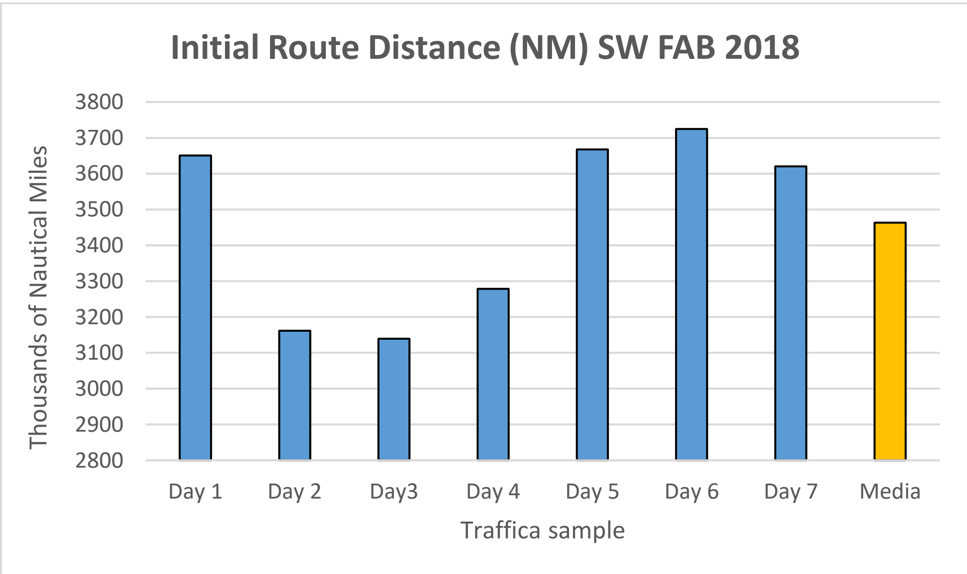

Figure 5.7 SW FAB initial distance in 2018

In the case of free-route distance (see Figure 5.8), the mean equalled approximately 3,45 million NM, showcasing a behaviour similar to the highest and lowest values in the same days.

Comparing initial and free-route means, the difference approximated 0,4%. Applied at the macroscopic level, this represents a considerable distance saving per day.

Results from free-route distance for 2018 traffic samples are presented in Figure 5.8:

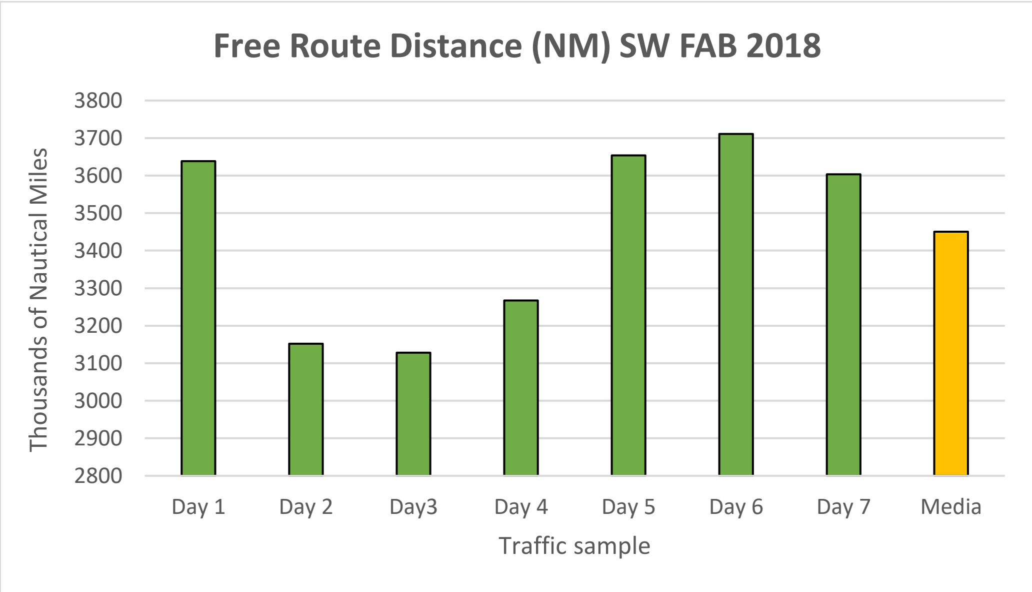

Figure 5.8 SW FAB free-route distance in 2018

Traffic samples from 2024 (see Figure 5.9), meanwhile, demonstrate an increase of another 600 flights compared to 2018 samples. Here, the mean of flights reaches around 2656.

The day-one traffic sample represents the highest peak, with approximately 2942 flights and deviating approximately 10% from the mean.

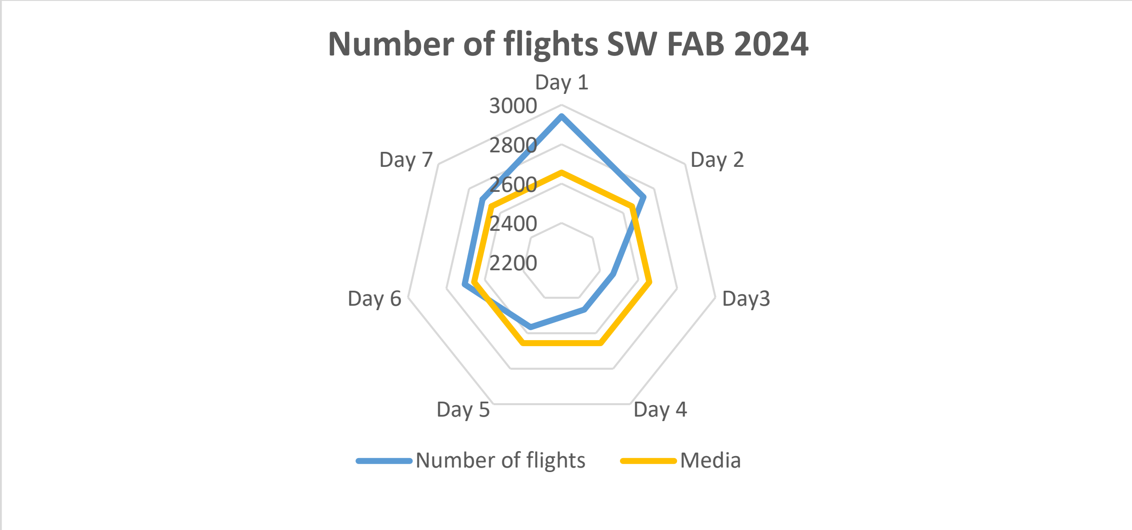

Figure 5.9 SW FAB number of flights in 2024

Correlating with this increase in flights, the increase in flight distance described in the next figure illustrates an increase in the mean, with samples from 2024 producing a flown mean of 4,57 million of NM. The following graphic (see Figure 5.10) illustrates the flight distance values for 2024 traffic samples.

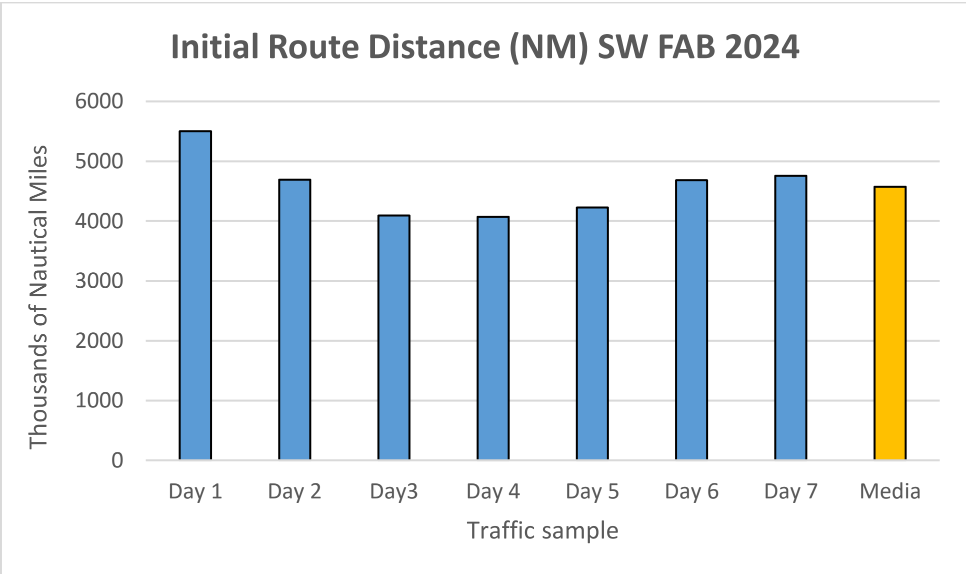

Figure 5.10 SW FAB initial distance in 2024

Compared to free route, 2024's flown distance illustrates a decrease of 4,56 million of NM from the initial scenario.

According to Figure 5.11, the values' behaviour closely resembles the initial samples without any notable deviations from the values' mean.

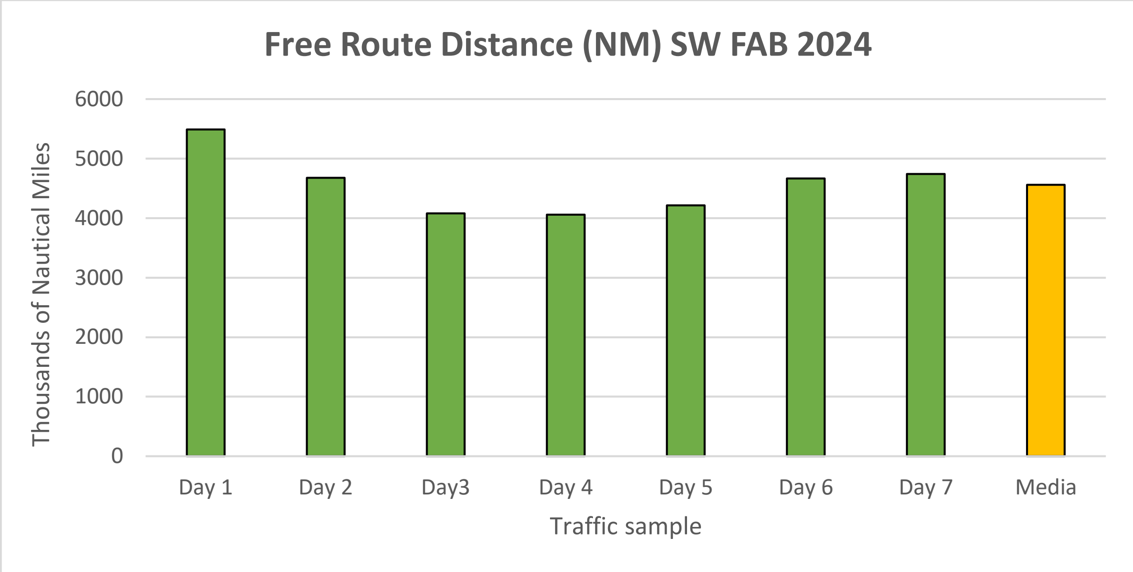

Figure 5.11 SW FAB free-route distance in 2024

The analysis of distance savings and flight time corresponding to the values presented in this section are illustrated in sections 5.2.3 and 5.2.4.

Based on the mean of the seven traffic samples used per scenario, savings for SW FAB users will approximate the potential benefits for airspace users, such as airlines.

The vast extension of the Southwest FAB is expected to generate a number of benefits, but it is important to mention that simulated traffic flows are based on trajectories from origin to destination airports and are mainly oriented towards and from Canary FIR. No remarkable traffic flow crosses Santa Maria Oceanic but, based on free-route concept, the flights that cross this airspace will benefit the most, because those flights feature greater flown distances.

5.2.3. SW FAB Distance Saving Results

Similar to previous works (Nava-Gaxiola, C.; Barrado, C.; Royo, P., 2018), (Nava-Gaxiola, C.;Barrado, C.; Royo, P. and Pastor, E., 2018) (Nava-Gaxiola & Barrado, 2016), free-route benefits are clearly noted by airspace users.

In this sense, the larger the area from free-route application, the greater the benefits for airspace users (Henn, A., 2015), representing the main advantage of free-route implementation in the Southwest FAB.

Simulation results indicate that, as considerable traffic load flies the SW FAB, more distance savings are incurred.

As depicted in Table 5.1, for 2012, featuring 1459 flights, distance savings are estimated at 10269 NM, corresponding to 0,42% in savings compared to the initial scenario. Then, 2018 and 2024, possessing higher traffic loads of 2076 and 2656 flights, respectively, the estimated benefits are increased from approximately 12800 to 14400 NM.

Table 5.1 SW FAB distance savings

Scenario	2012	2018	2024
Initial route distance (NM)	2473923	3463235	4574163
Free route distance (NM)	2463654	3450466	4559743
Distance savings (NM)	10269	12769	14420

Results from last table are expressed in Figure 5.12, where the decrease in distance-saving ratio is notable.

Regarding this slight decrease from 0,42 to 0,32% compared to the main SW FAB traffic flows discussed in previous sections, it could be that these decreases are based on the airspace's structural limit and the configuration of trajectories. This means that, as trajectories are formed from city pairs (origin and destination) and considering the geographical locations of the airports between the Canary Island, Portugal and Spain and Northern countries, flows are clearly defined only through Lisbon FIR and Canary FIR, concentring the main traffic. This behaviour of traffic flows in turn demonstrates that the SW FAB's structure remains limited.

Adding to this, the highest traffic load for 2024 consists of 54% of the flights from 2012 (see Figure 5.12).

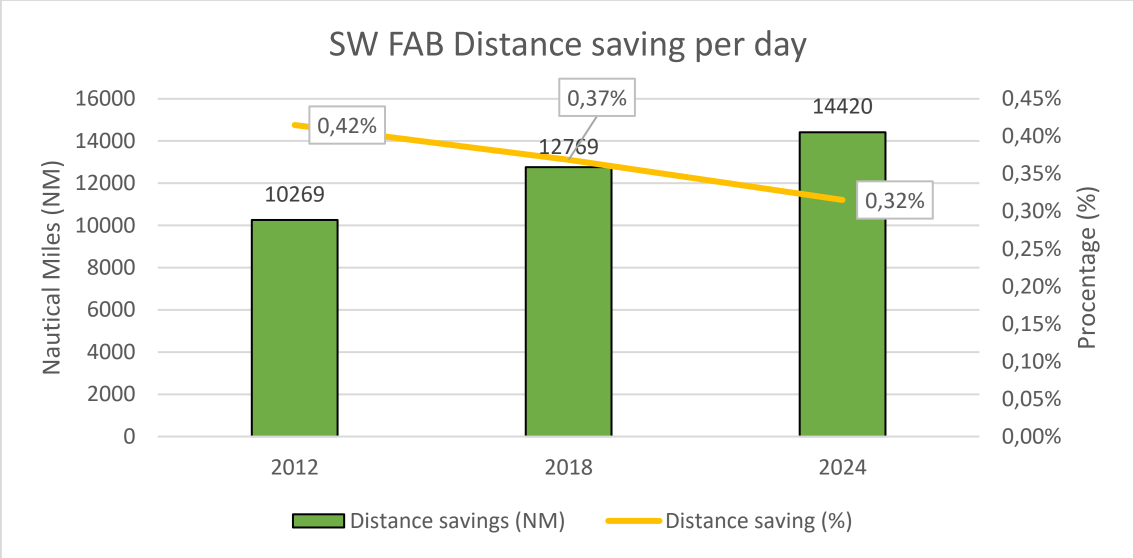

Figure 5.12 SW FAB distance savings

From Figure 5.12, it can be summarised that free route presents daily distance savings for airliners. Furthermore, it is easy to note that the ratio of benefits decreases as the traffic increases, demonstrating the structural limit of the SW FAB.

5.2.4. SW FAB Flight Time Savings Results

Translating the simulation results to flight time, benefits exhibit similarities to distance savings. These remain favourable for all cases, increasing from 85 flight hours with traffic load from 2012 to 179h in 2024, nearly 100% more (see Table 5.2).

Regarding fuel savings, the results indicate that for 2012 traffic, approximately 106 fuel tons can be saved, reaching approximately 224 fuel tons for the highest number of 2024 flights.

Estimations for emissions (CO2 and NOx) indicate that free-route implementation could reduce C02 emissions from 334 to 703 tons per day.

Table 5.2 SW FAB flight time savings

Measure	2012	2018	2024
Flight time saving (h)	53,0	86,5	111,7
Fuel saving (tons)	106,3	173,4	223,9
CO2 emissions (tons)	333,7	544,5	703,1
NOx emissions	0,9	1,4	1,8
NOx emissions (tons/0,01)	85,0	138,7	179,1

For simplicity, previous results are presented in Figure 5.13, demonstrating the benefits for airspace users and the environment from applying full free route to the SW FAB.

As depicted in the following figure, flight time savings range between 3,22 and 3,92% compared to the initial values and estimating per day.

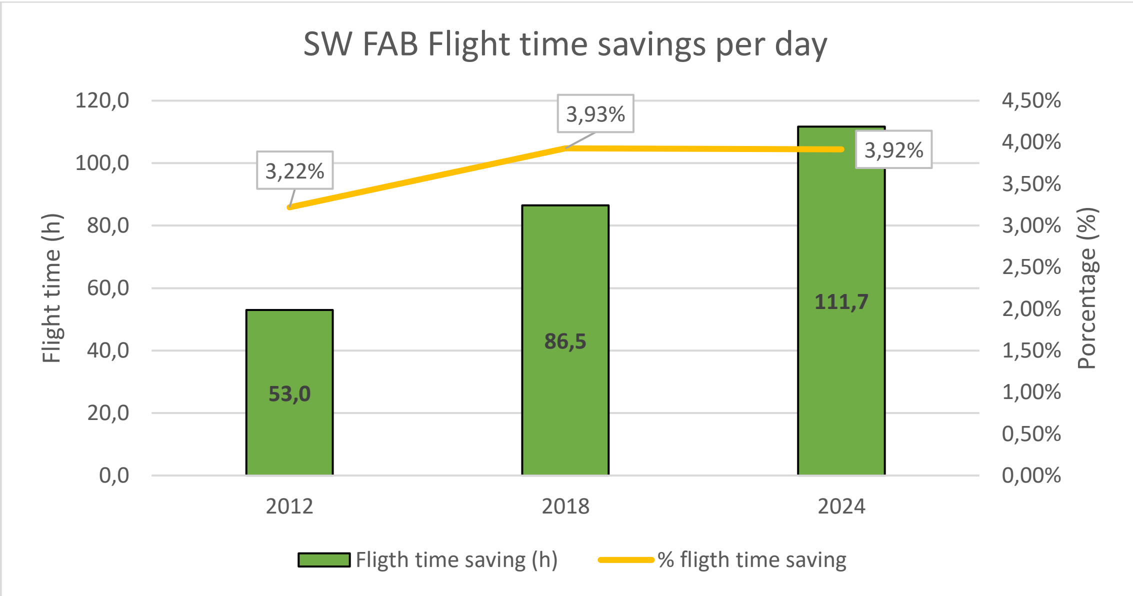

Figure 5.13 SW FAB flight time savings

The relations of fuel and emission savings are provided in the following figure, where to can be noted that the effects of emission savings resulting from CO2 emissions reach values of 700 tons per day with traffic estimation from 2024.

For NOx emissions, the graphic illustrates a relation (10 times less) for the possible savings. There, results indicate benefits from 850 to 1790 kg (see Figure 5.13).

Figure 5.14 below demonstrates free route's benefits in terms of fuel and emission savings, estimating values per day:

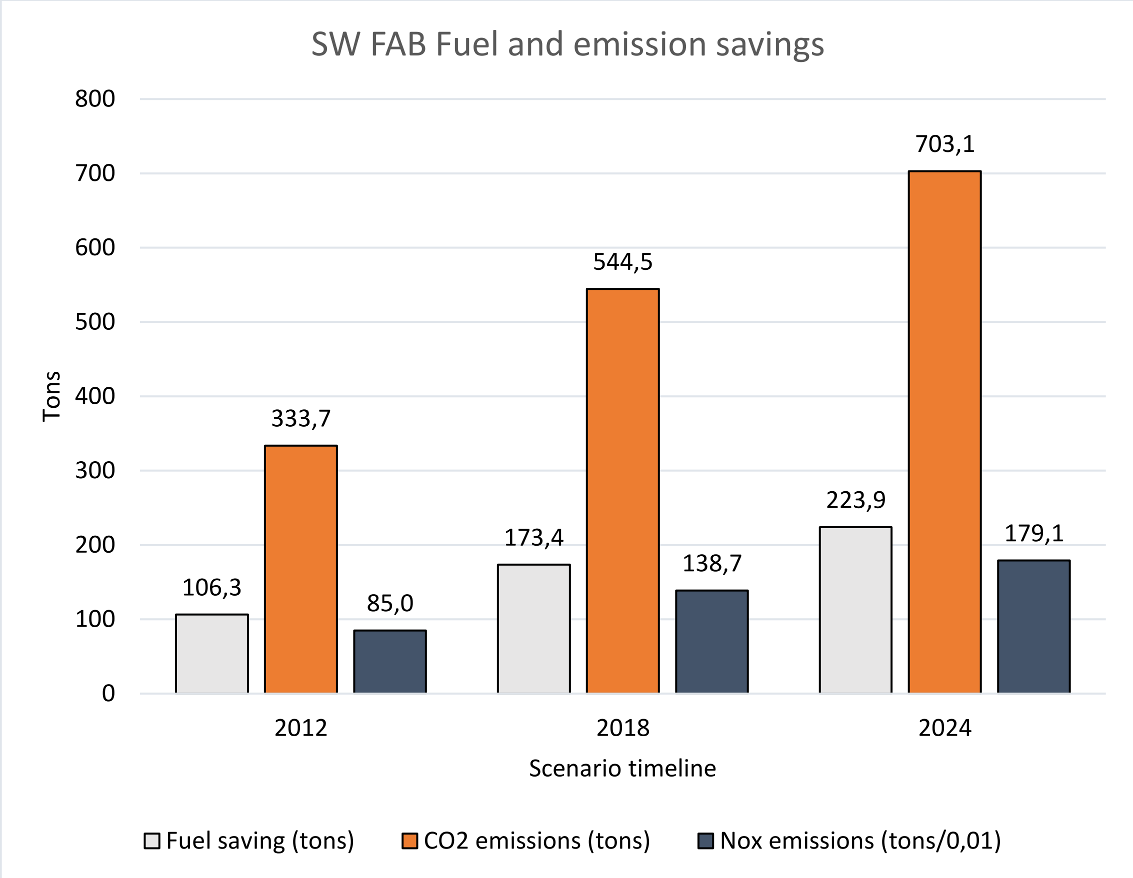

Figure 5.14 SW FAB fuel and emission savings

Benefits from free-route implementation in the SW FAB were demonstrated in previous section in terms of distance, flight time, and fuel and emission savings. Nonetheless, these benefits could also be translated to economical savings and final user gains for passengers and the natural environment.

5.2.5. SW FAB Conflict Results

The study of conflicts, as the first indicator, provides an overview of conflicts introduced to the airspace by implementing free route in the SW FAB. In this sense, by comparing the potential conflicts between both scenarios (2018 and Full FRA) and analysing the increases or changes in conflict dimensions, such as vertical and horizontal, it is possible to determine the challenges that free-route implementation produces.

The general results presented in Figure 5.15 indicate that the number of conflicts is reduced as considerable traffic load is simulated.

For the conflict indicator, it is crucial to note that a strength relation occurs between conflicts and traffic loads, where conflicts are entirely calculated as losses of separation standards, directly affected by changes in density produced by the increases or decrease in flight numbers. Consequently, one way in which this thesis determines these effects is by evaluating the airspace and effects on traffic behaviours as conflict indicators.

Nonetheless, the improvements in the number of conflicts demonstrated in Figure 5.15, and considering the SW FAB simulations, indicates that conflicts are reduced from 2012 to 2024 scenarios, suggesting that free route lowers the number of conflicts by 22–26%.

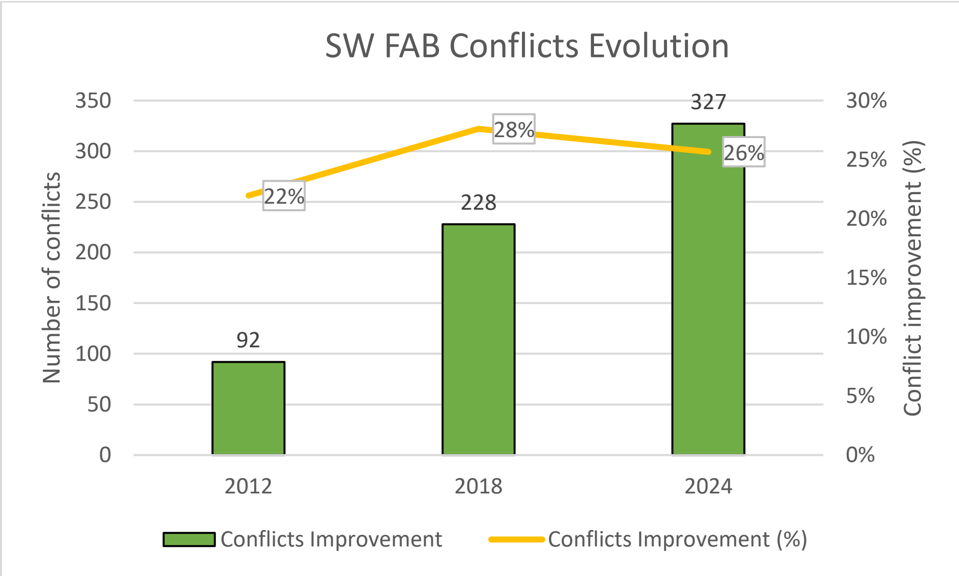

Figure 5.15 SW FAB conflict results

5.2.5.1. Detailed conflict scenario SW FAB 2012

The study of conflicts in 2012 presented in Figure 5.16 demonstrates the number of conflicts and differences per each traffic sample. For all traffic samples described, the number of conflicts is reduced from 12 to 30%.

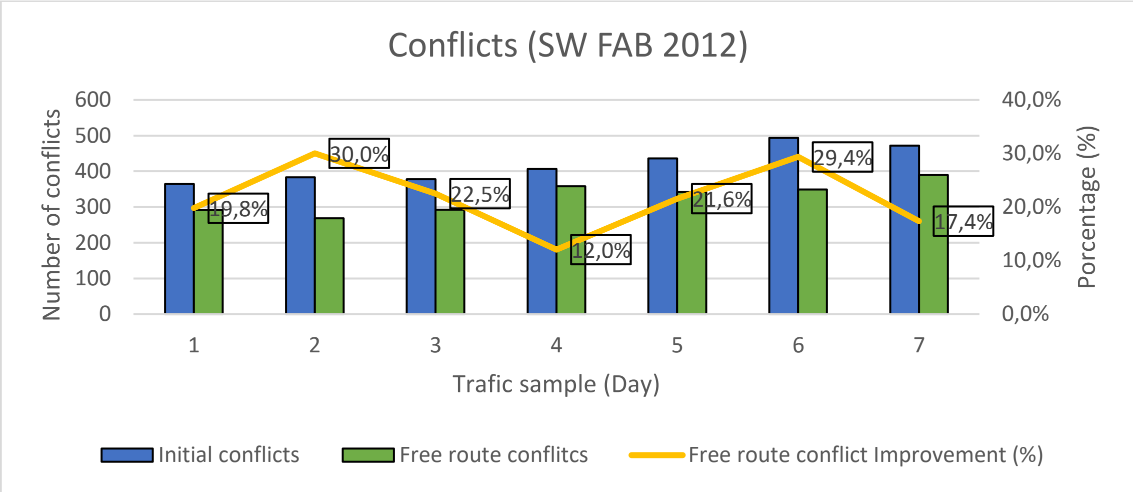

Figure 5.16 SW FAB conflicts in 2012 per traffic sample

For the vertical dimension of conflict study, in the SW FAB, Figure 5.17 presents the results for traffic samples from 2012. This figure illustrates that the increase in cruise/cruise conflicts corresponds to a global increase in the horizontal dimension conflicts.

On the other hand, there is an approximate increment of 28% in the conflicts for evolving/evolving, meaning that free route increases the vertical interactions of the mixture of climbing and descending.

In the case of evolving/cruise conflicts, free route and traffic samples from 2012 feature a decrease in the number of conflicts by roughly 42%.

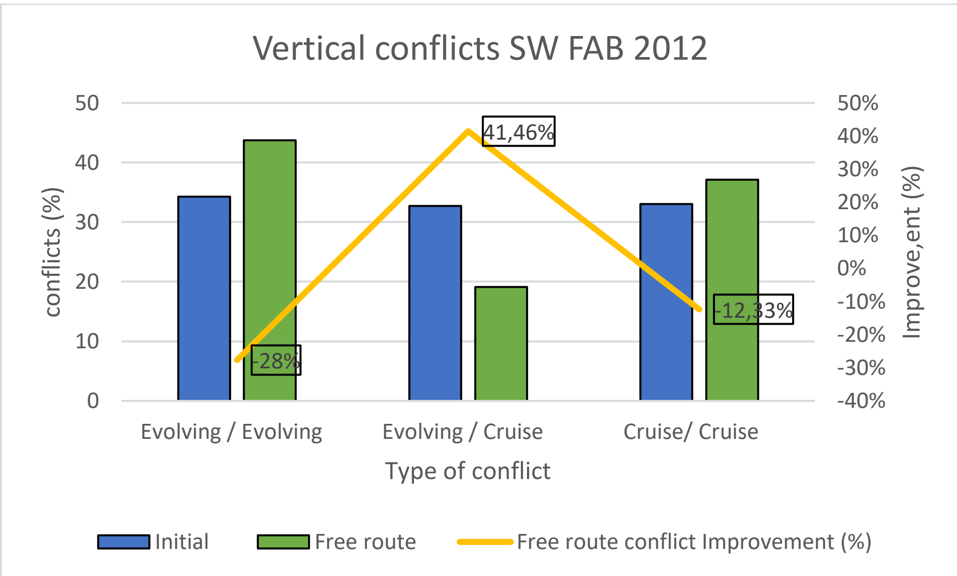

Figure 5.17 SW FAB vertical conflicts in 2012

Regarding the horizontal dimension, simulation results indicate that crossing conflicts are increased by 37%, and consequently, parallel and opposite are reduced (see Figure 5.18).

As previous results demonstrated in this thesis, the increase in crossing trajectories represents an expected effect from free-route implementation, which produces a more random scenario from the perspective of horizontal dimension trajectories. Adding to this, as traffic loads are increased (2018 and 2024), it is also expected to experience at least the same magnitude of crossing conflicts.

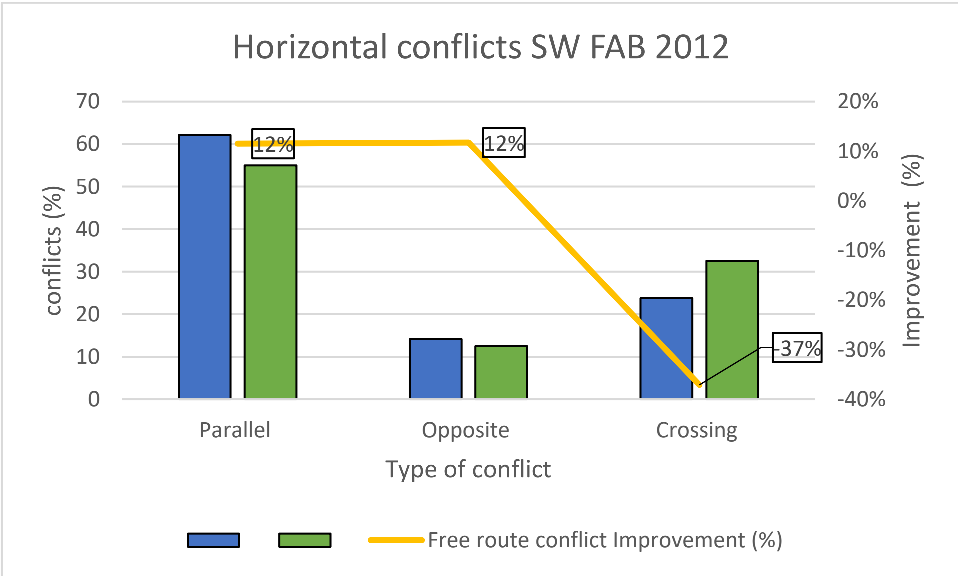

Figure 5.18 SW FAB horizontal conflicts in 2012

The global results and distribution of conflicts in 2012 (see Figure 5.19) illustrate that implementing free route increases evolving/evolving conflicts, particularly those related to parallel trajectories. In this sense, the increase equals around 15% compared to the initial traffic, but the remarkable result concerns its weight in the global number, passing from 25 to 30% of the total conflicts.

On the other hand, cruise/cruise crossing passes from less to 10% to 17%. For the global number of conflicts, this means a 38% increase in this type of conflict compared to the initial traffic sample.

Figure 5.19 illustrates the global distribution of conflicts and how it differs from 2012 traffic simulations:

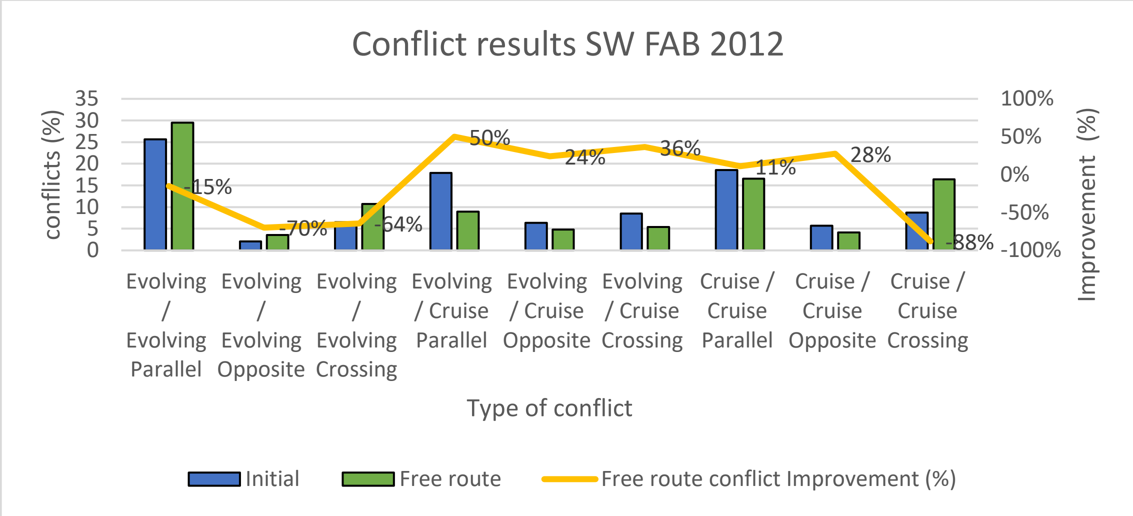

Figure 5.19 SW FAB total conflict results in 2012

5.2.5.2. Detailed conflict scenario SW FAB 2018

From the second set of traffic samples, corresponding to 2018, simulation results indicate a notable decrease in conflicts, around 24 to 31%, distributed across the seven traffic samples.

The previously noted reductions mean that approximately 100–200 potential separation losses are reduced with full free-route implementation compared the SW FAB.

Figure 5.19 presents the total number of conflicts per traffic sample in 2018:

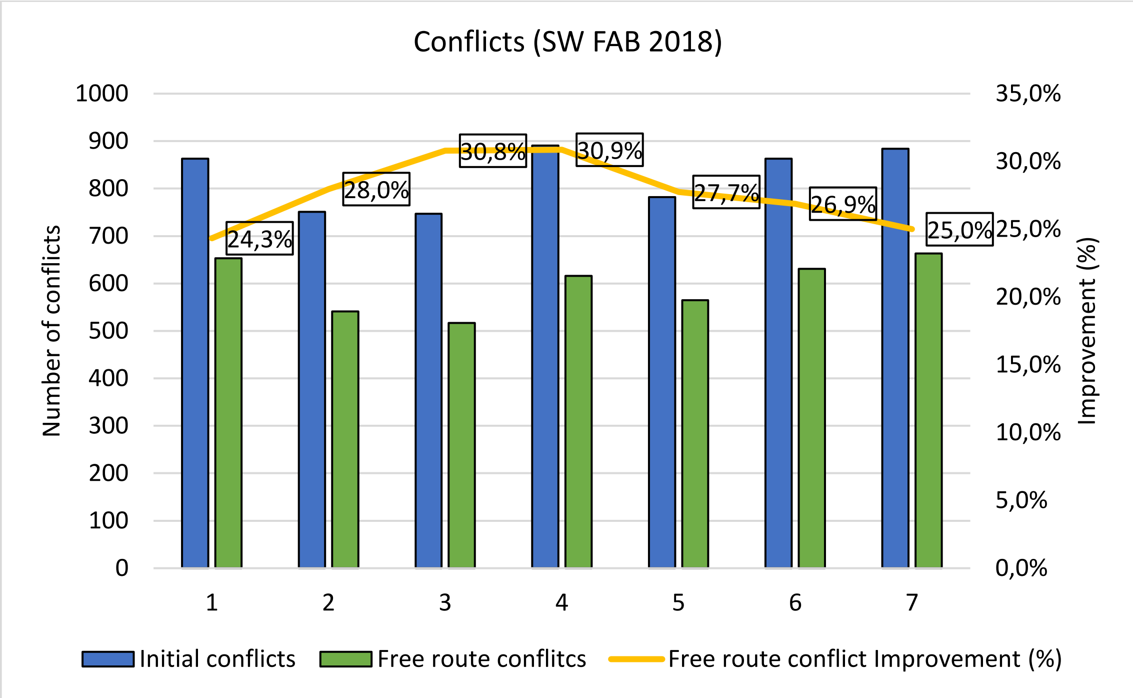

Figure 5.20 SW FAB conflict results per day in 2018

From the vertical dimension for the 2018 traffic samples, simulation results indicate a remarkable increase of approximately 42,5% in the cruise/cruise conflicts, meaning that horizontal dimension trajectories are affected.

Meanwhile, evolving/evolving conflicts result in approximately 11,5% increases, and subsequently, evolving/cruise conflicts are reduced by approximately 47,6%.

Figure 5.21 illustrates the conflicts for the vertical dimension in the SW FAB scenario:

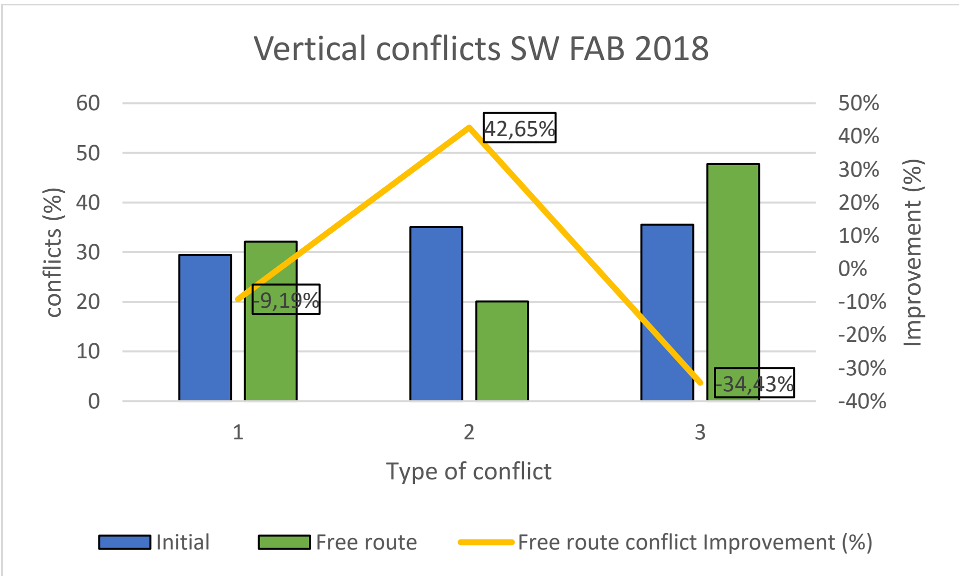

Figure 5.21 SW FAB vertical conflicts in 2018

For horizontal conflicts, and resembling previous results, the crossing conflicts are increased by around 33%. This in turn reduces parallel and opposite conflicts to balance the increases, as mentioned before.

Figure 5.22 presents the conflict in the horizontal dimension for traffic samples from 2018 in the SW FAB:

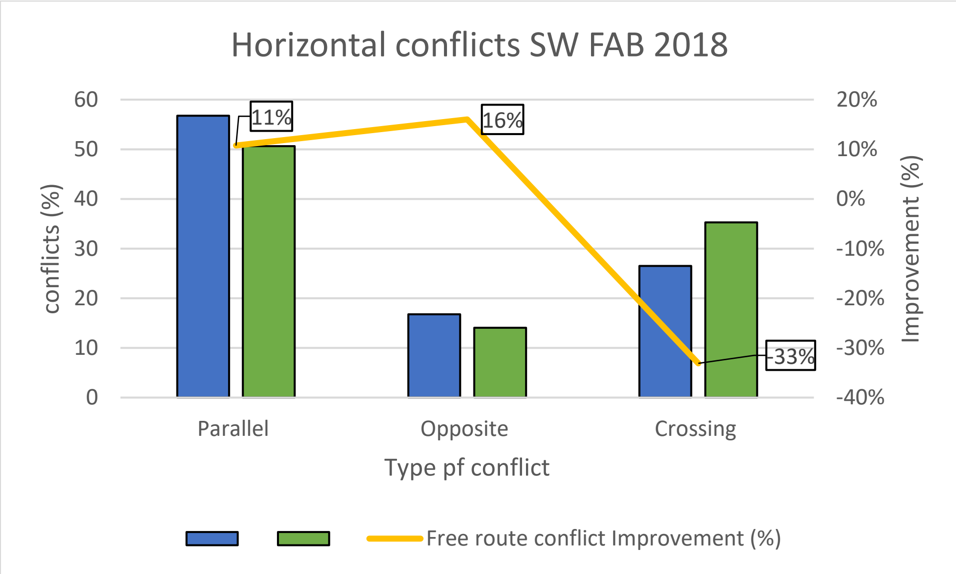

Figure 5.22 SW FAB horizontal conflicts in 2018

The global number of conflicts in 2018 is presented in Figure 5.23. Here, the distribution of conflicts supports previous results. The most notable increase relates to cruise/cruise/crossing trajectories, which increase by approximately 118%, passing from 10% to 20% of the total number of conflicts.

Similar results are produced for cruise/cruise/opposite, where an increase of 60% represents 4% more total conflicts.

Regarding vertical conflicts, the evolving/evolving/parallel conflicts present an increase of 15%, meaning 2–3% more in the global number.

It is easy to note that evolving conflicts improves, meaning that the mix of traffic climbing and descent is reduced with free route (see Figure 5.23).

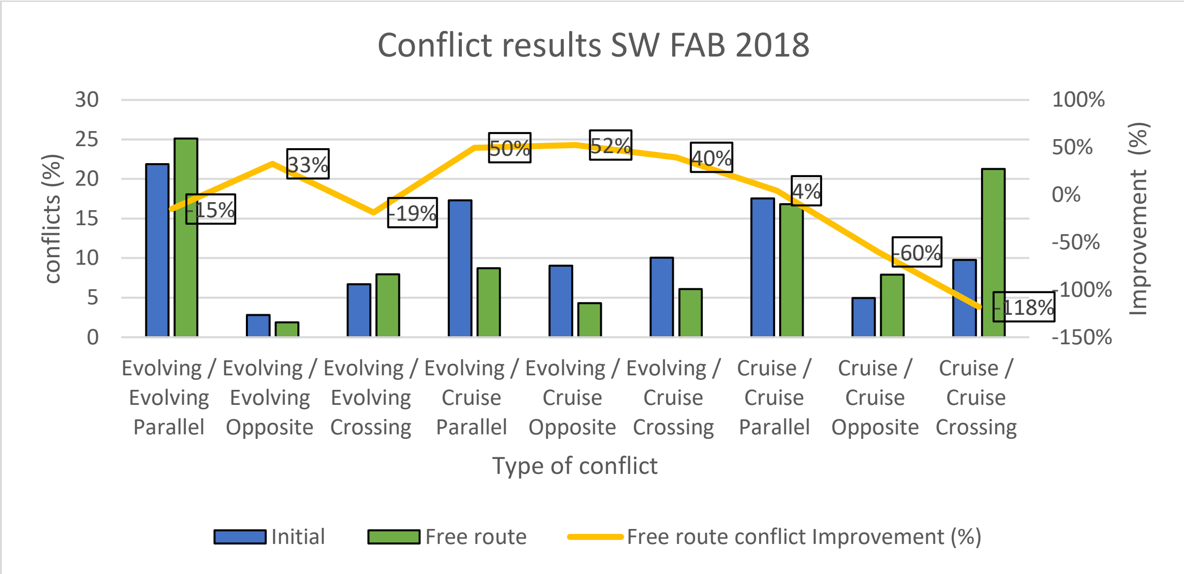

Figure 5.23 SW FAB total conflict results in 2018

5.2.5.3. Detailed conflict scenario SW FAB 2024

For simulations from 2024, Figure 5.24 represent the total number of conflicts. Here, results demonstrate similarities with previous scenarios with reductions between approximately 19 and 31%.

In the case of day five, reduction equalled about 30,6%, meaning 400 fewer conflicts. In line with this, most of the traffic samples presented reductions between 200 and 400 conflicts.

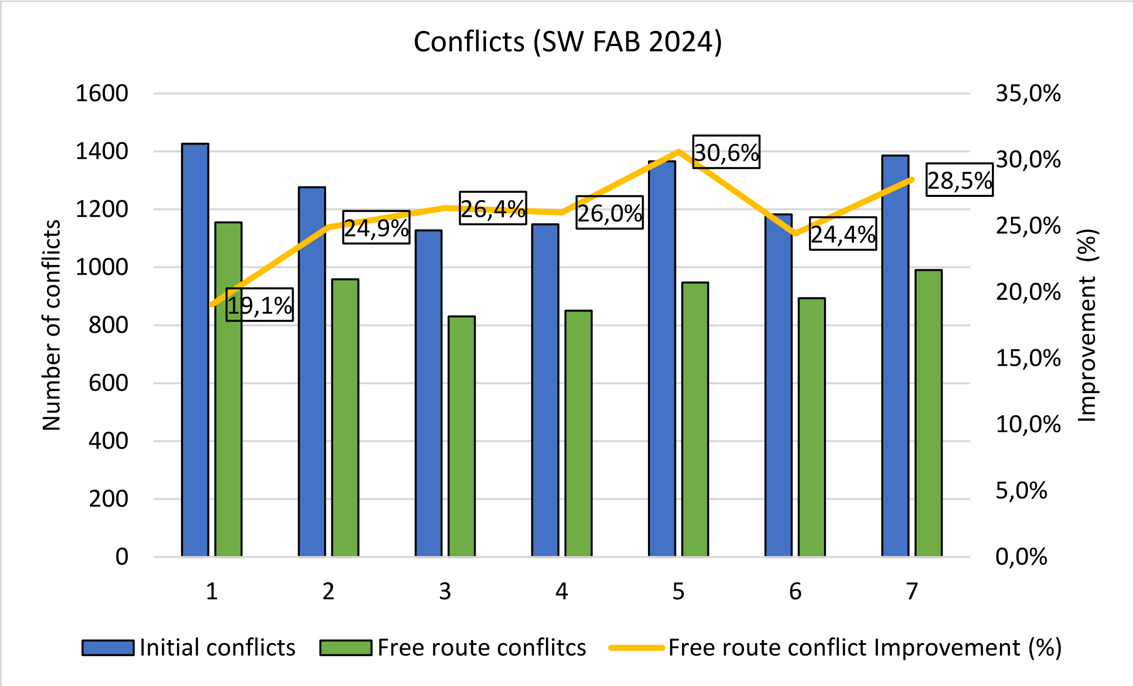

Figure 5.24 SW FAB conflict results per day in 2024

The study of vertical conflicts in 2024 are presented in Figure 5.24, where the cruise/cruise conflicts increase by 34%, representing approximately 50% of the total conflicts in the vertical dimension.

On the other hand, a notable reduction of 43% occurs for the evolving and cruise conflicts, meaning better stratification by FL of the trajectories with free route.

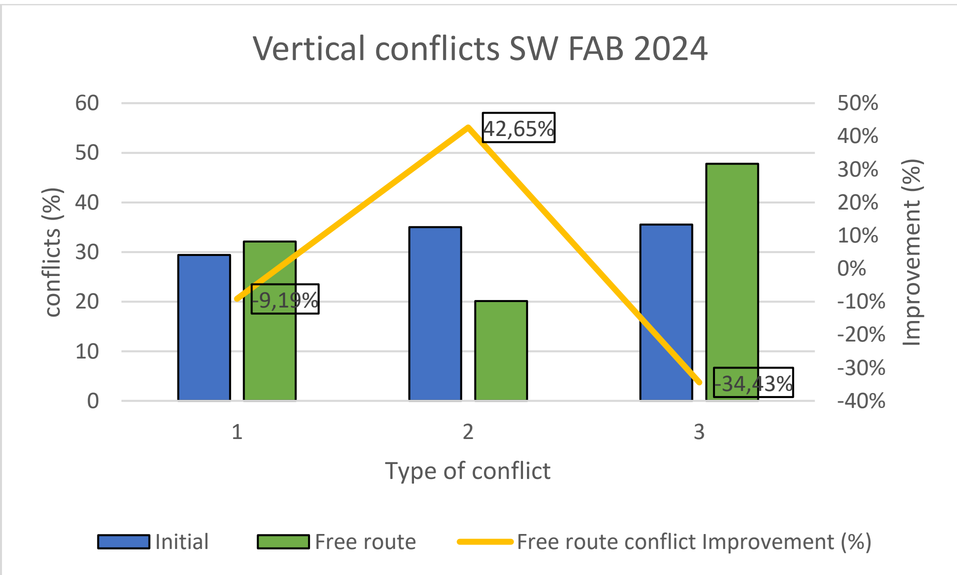

Figure 5.25 SW FAB vertical conflict results in 2024

In line with Figure 5.26, results from the horizontal dimension in 2024 indicate that the absolute value in crossing conflicts is increased by 36%. Consequently, it represents approximately 10% of the total conflicts.

Due to the increase in crossings, parallel and opposite are reduced by 13,9 and 11,04%, respectively.

Figure 5.26 presents the distribution of horizontal conflicts using the traffic samples from 2024 in the SW FAB scenario:

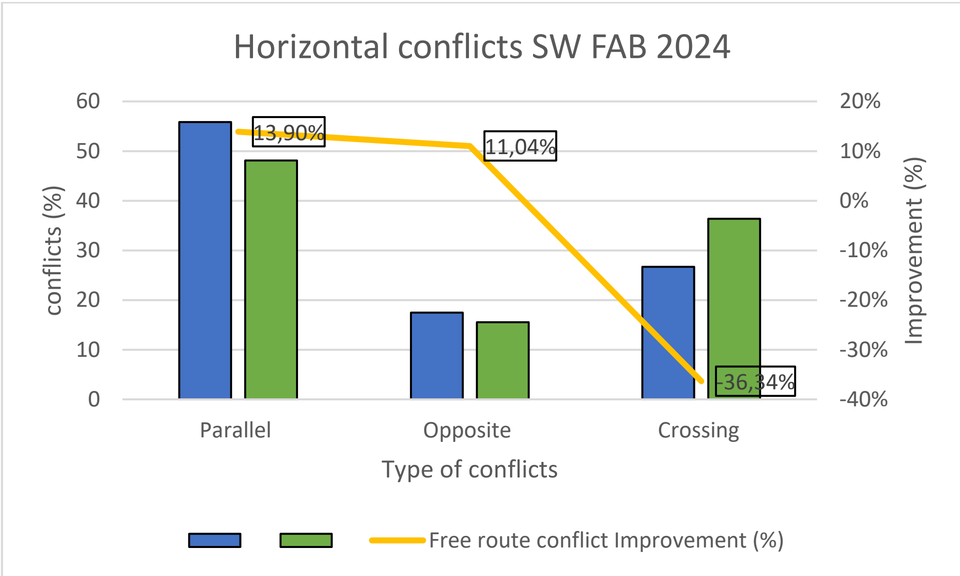

Figure 5.26 SW FAB horizontal conflict results in 2024

The results presented in Figure 5.27 indicate that cruise/cruise crossing conflicts have increased by 113%, producing an increase of 10–21% of the global. Additionally, cruise/cruise/opposite conflicts are increased by 53%, reaching around 3% of the total.

Another remarkable result is that evolving/evolving/parallel conflicts increased by 11%, as did evolving/evolving crossing. These results do not affect the global number of conflicts, however, and so can be considered debateable.

Figure 5.27 illustrates the overall conflict distribution by type, relating traffic samples from 2024 and the SW FAB scenario:

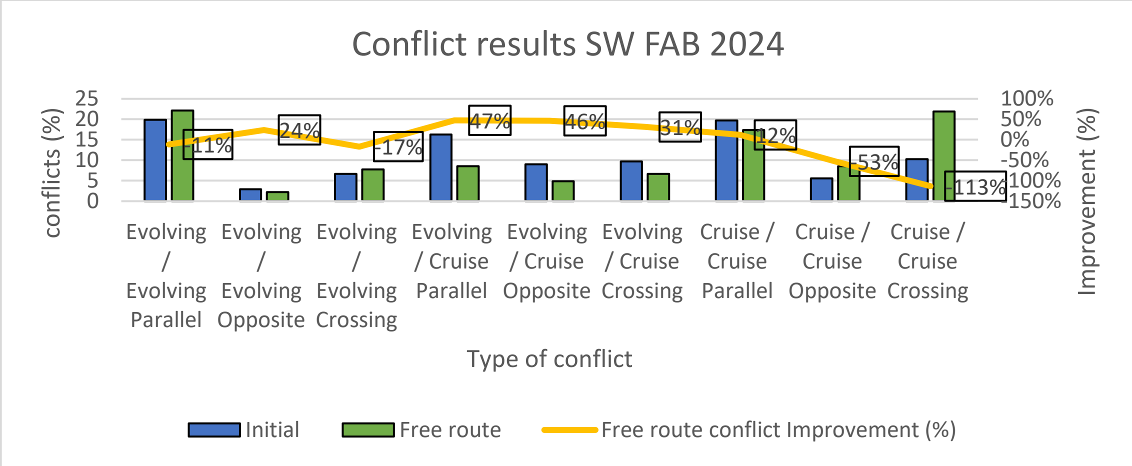

Figure 5.27 SW FAB total conflict results in 2024

As mentioned previously, the conflict indicator directly relates to traffic characteristics; thus, any change in traffic behaviour could be rapidly noted by this indicator. However, this is not sufficient to describe the environment's complexity.

For that reason, the complexity section, based on adjusted density in the interactions concept, defines how complex the airspace is made, and with similar tendencies to the presented conflicts analysis.

5.2.6. SW FAB Complexity Results

The complexity study in the SW FAB scenario is based on the metrics discussed in chapter three. Like previous NEFRA calculations, this complexity analysis aims to estimate the complexity score and structural index to understand the effects of full free-route simulation in the SW FAB area.

5.2.6.1. SW FAB Adjusted density

First, calculations are focussed on identifying the adjusted density based on the relation between interactions and flight-controlled hours per cell. The investigated metrics produce estimations of interactions according to each dimension: vertical, horizontal and related to speed.

Relating global interaction and flight hours influenced by adjusted density and dimensional interactions, it is possible to discern the relative indicators and structural index.

Finally, as in the previous chapter, the complexity score offers a global estimation indicating how complex or 'difficult' the airspace in question is made.

The general overview of interactions and traffic volume is provided through the adjusted density. The following figure illustrates the adjusted density from the SW FAB for each traffic sample:

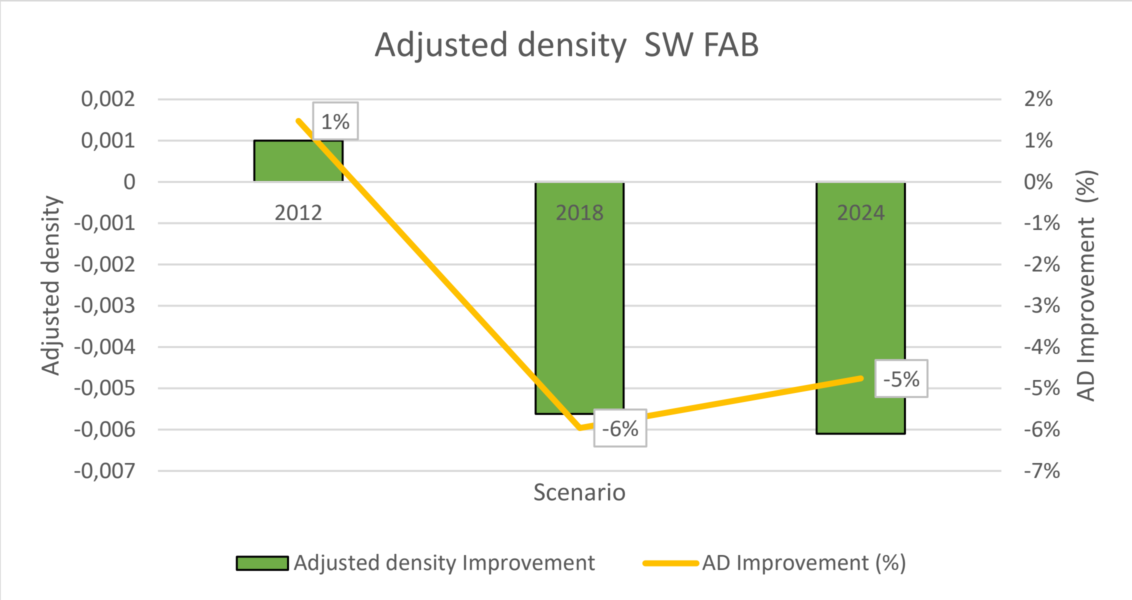

Figure 5.28 SW FAB Adjusted density

As can be seen in Figure 5.28, introducing full FRA in the simulations results in penalisations for adjusted density. From these results, it is possible to state that interactions in 2018 and 2024 are growing or spread across a high ratio compared to the traffic or number of flights (volume of flight-controlled hours).

The following figures provide an exhaustive analysis of adjusted density in each traffic sample.

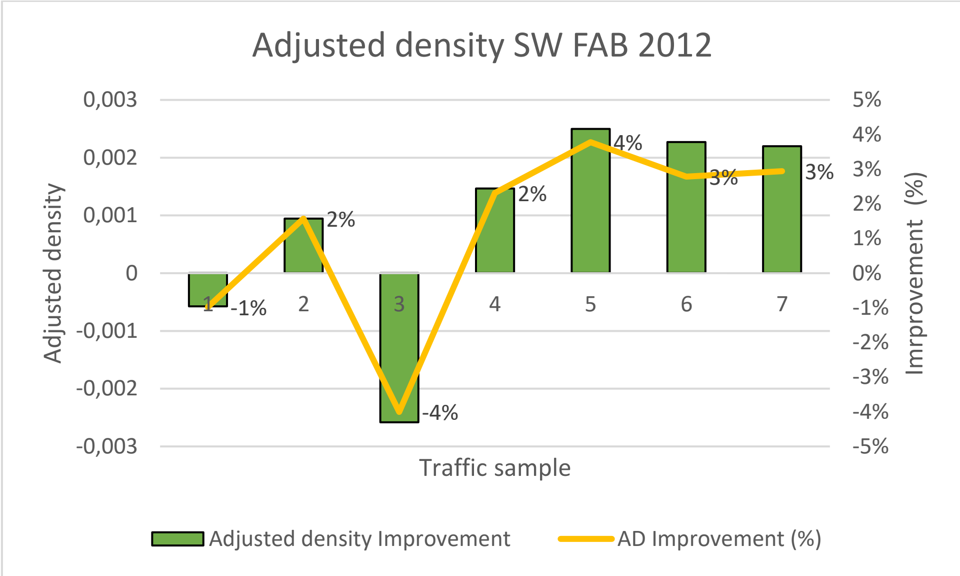

Figure 5.29 SW FAB adjusted density in 2012

Figure 5.29 illustrates the adjusted density for each traffic sample from 2012, where it can be noted that, in general, values are positive and approximate 3%. This means that free route produces effective results in terms of interactions; in other words, interactions are not growing as controlled flight hours.

Figure 5.30 below presents the adjusted density results corresponding to the traffic samples from 2018. Here, it can be observed that FRA adjusted density is mainly negative or increased compared to the initial scenario.

These negative values can be explained by the fact that the quotient interactions presented with the FRA's introduction are larger than those evaluated from the initial traffic.

It should also be noted that the values from Figure 5.30 only represent the interactions per ratio of controlled flight hours, while a deeper analysis concerning which type of interactions and complexity is presented in the following analysis.

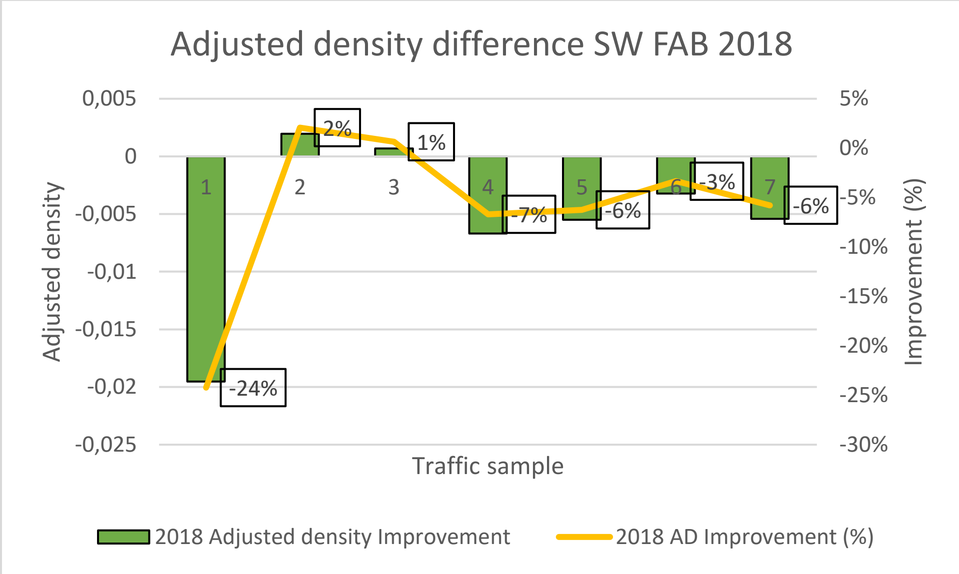

Figure 5.30 SW FAB adjusted density in 2018

For 2024, results similar to those from previous traffic samples are presented in Figure 5.31.

The adjusted density from 2024 suggests that all differences are negative, meaning that interactions experience notable growth with the free-route simulations.

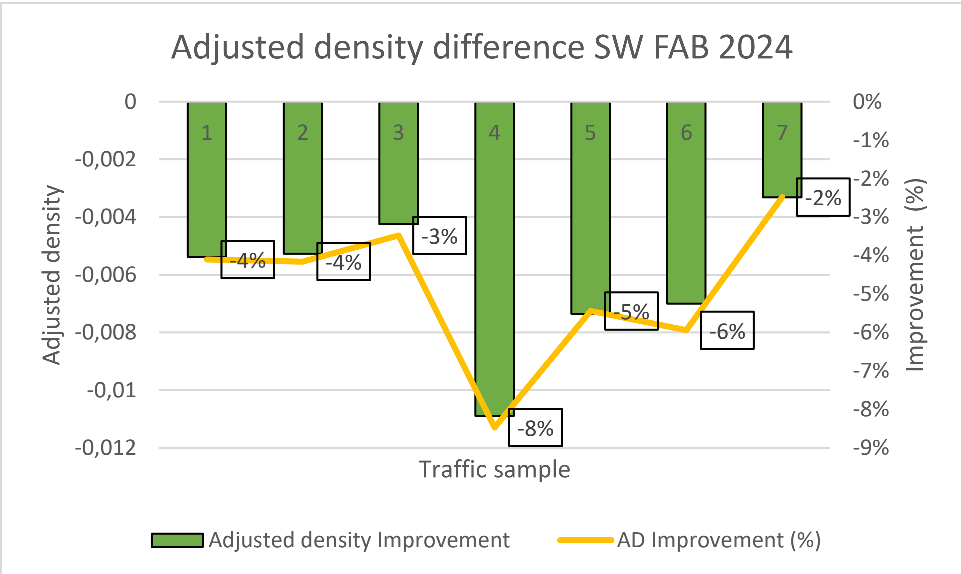

Figure 5.31 SW FAB adjusted density in 2024

5.2.6.2. SW FAB Complexity Indicators

The complete study of complexity is based on analysing global interactions and volume of hours, as well as an independent study of each type of interaction, resulting in the complexity score.

Figure 5.32 illustrates the vertical indicator results, demonstrating improvements with the free-route application. In this sense, results in the vertical dimension indicate that, with the traffic sample from 2012, a decrease in vertical interactions of around 37% occurs.

In addition, traffic samples from 2018 and 2024 present improvements estimated at 62 and 44%, respectively.

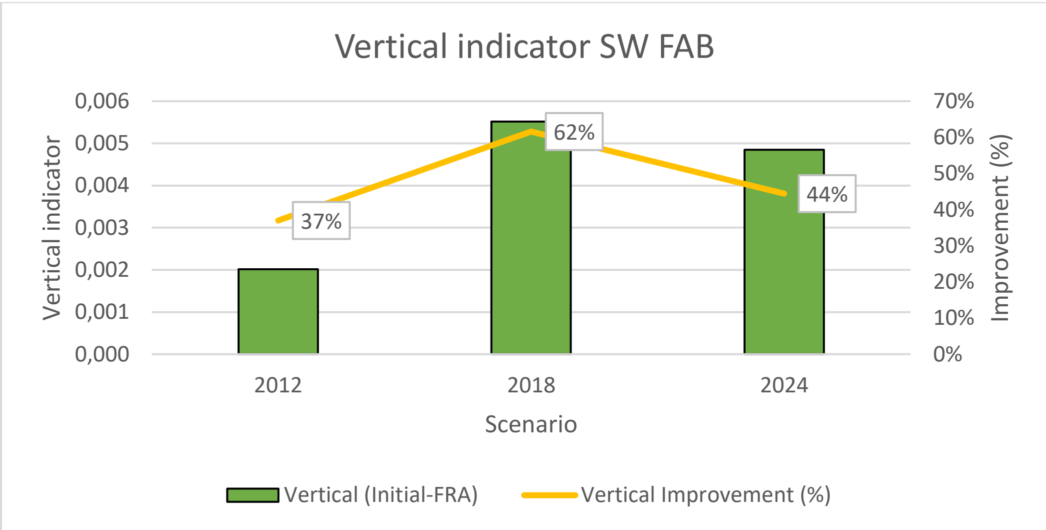

Figure 5.32 SW FAB vertical indicator results

For the horizontal indicator (see Figure 5.33), free-route implementation demonstrates negative values, meaning that the horizontal interactions derived from crossing trajectories increased. These results are clearly supported by previous values from conflict distribution.

The results showcased in Figure 5.33 and corresponding to the horizontal interactions are explained through the random behaviour behind the preferred routes offered by free route rather than the use of ordinary airways.

Simulation results indicate that, for traffic samples from 2012, the increase in horizontal interactions reaches approximately 16% while, for the highest traffic loads in 2018 and 2024, values approximate 19 and 20%, respectively.

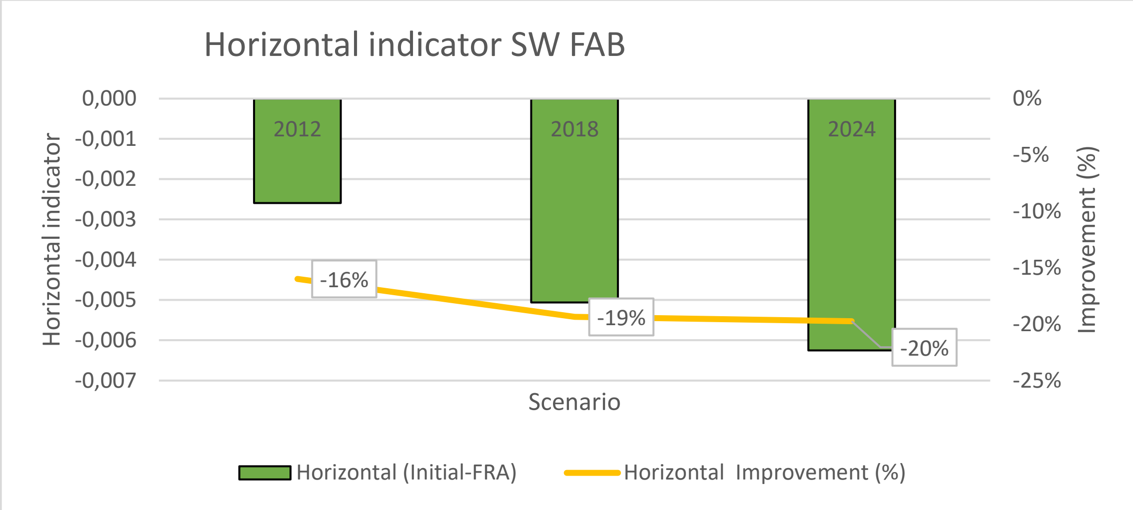

Figure 5.33 SW FAB horizontal indicator results

The third indicator, related to speed interactions, is presented in Figure 5.34. From this, it can be noted that, after free-route simulations, values related to speed interactions decrease from 24 to 79% for each traffic sample.

Figure 5.34 summarises the results for the speed indicator and the SW FAB scenario.

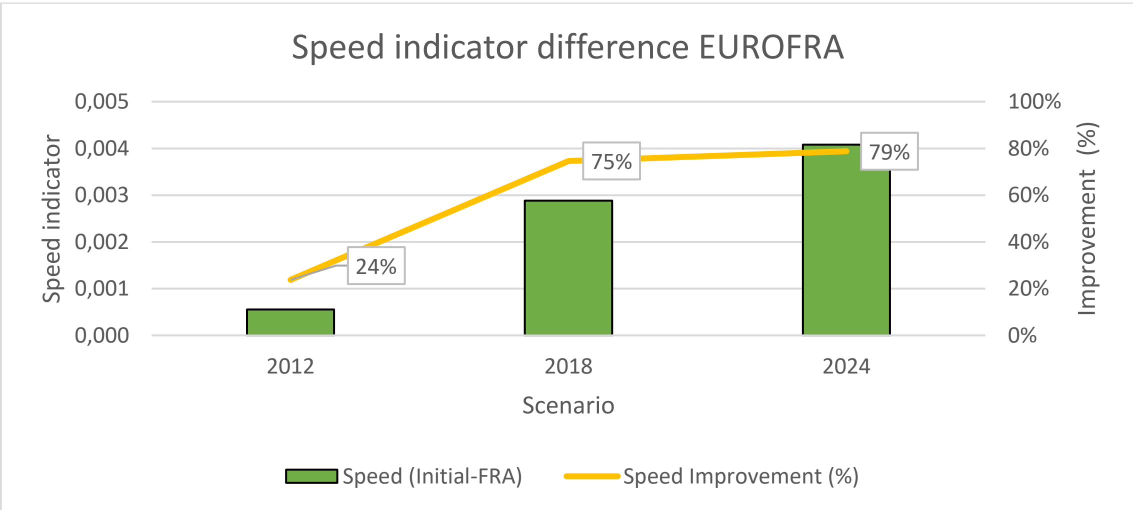

Figure 5.34 SW FAB speed indicator results

5.2.6.3. SW FAB Structural Index and Complexity Score

The structural index synthesised all values related to vertical, horizontal and speed interactions. The evolution of this indicator is presented in Figure 5.35.

From Figure 5.35, it can be stated that the simulated FRA demonstrated improvements in terms of specific interactions in vertical, horizontal and speed dimensions. Moreover, the representative values from 2,78% in 2012 and 12–13% in 2018 and 2024, respectively, indicate the structural limits of the SW FAB. This structural limit strictly relates to changes in vertical, horizontal and speed interactions, and not to the global value of interactions related to adjusted density.

With all this, it can be confirmed that, if we increase the traffic loads with a greater number of flights, the actual proposed SW FAB free-route scenario will experience negative effects in values of specific interactions, and consequently, its structural index. In this supposed case, the expected tendency will be to decrease the structural values, because the airspace will not lead with a possible propagation of horizontal (crossings) and will experience reductions in vertical and speed rather than gains, as previously demonstrated.

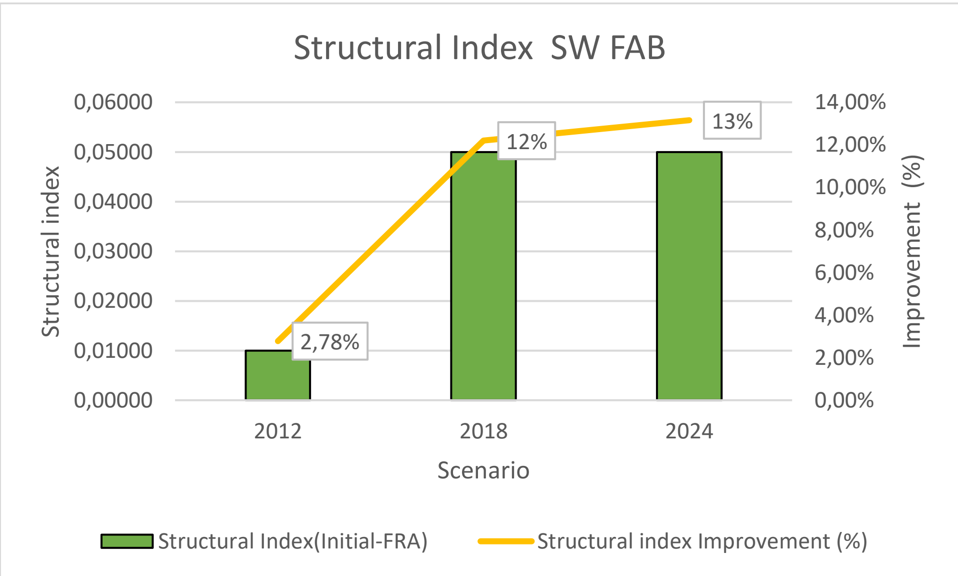

Figure 5.35 SW FAB structural index results

Finally, the global value of the complexity score in the SW FAB (see Figure 5.36) exhibits behaviour similar to the structural index, but here, values are related to adjusted density with the global interactions by cells.

As previously noted, results indicate improvements with free-route implementations. However, this study also finds a limit to these improvements, confirming the structural airspace limit for the SW FAB in terms of complexity.

Figure 5.36 presents the complexity score results with the SW FAB scenario:

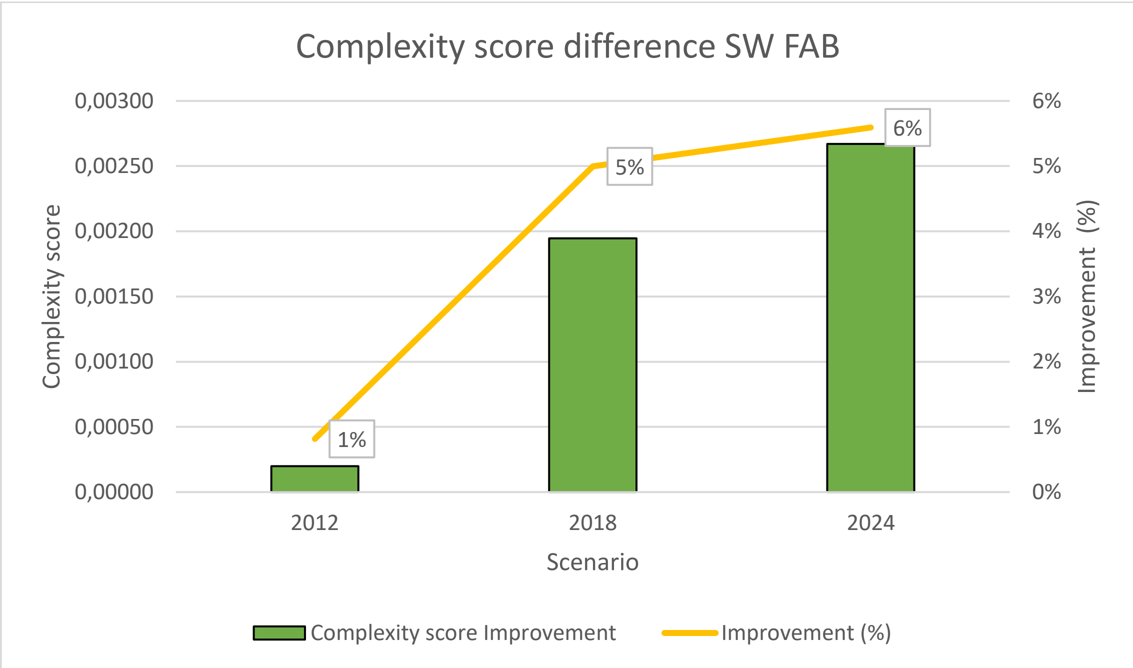

Figure 5.36 SW FAB complexity score results

The SW FAB study adds two important points to this thesis:

- The study of a larger airspace block using FRA.
- The analysis of an initial airspace structure with the Oceanic airspace, which is largely considered the origin of the free-route concept.

The SW FAB results illustrated the complexity limits of such a configuration, evidenced after simulated highest traffic loads in this airspace.

The following section will discuss the exploration of FRA, but with a larger airspace block, as well as with a futuristic waypoints network and adding more freedom than the SW FAB scenario.

6. EUROFRA Airspace

The next chapter describes all the results concerning the EUROFRA scenario simulations. Much like the previous chapters, the subparagraphs for chapter six are structured around the following points:

- Traffic characterisation (traffic samples)
- Route length and distance saving analysis
- Flight time and emission calculations
- Traffic conflicts
- Complexity study

6.1. Scenario Details

The EUROFRA scenario represents a futuristic scenario defined as a unique airspace block corresponding to the ECAC area and joining all the ACCs in Europe. This scenario is simulated in order to understand a future full implementation of a free-route area across Europe.

With EUROFRA's proposal of no borders, timing or flow restrictions, we aim to overcome the major portion of these limitations. To this end, this PhD thesis utilises the route-length metric to provide a broad analysis of the route extensions with the goal of assessing network efficiencies. This route-length computation utilises a spherical Earth model. The metric also solely examines the en-route part of the route; it does not consider the TMA route aspect in the route-length computation. To do so, it either subtracts a fixed route length for SID and STAR or removes the route part residing in the first 30 NM around departure and arrival airports (TMA route part extraction).

The vertical limits are compressed between FL250 and FL660. Figure 6.1 below depicts the EUROFRA airspace block as presented in NEST software:

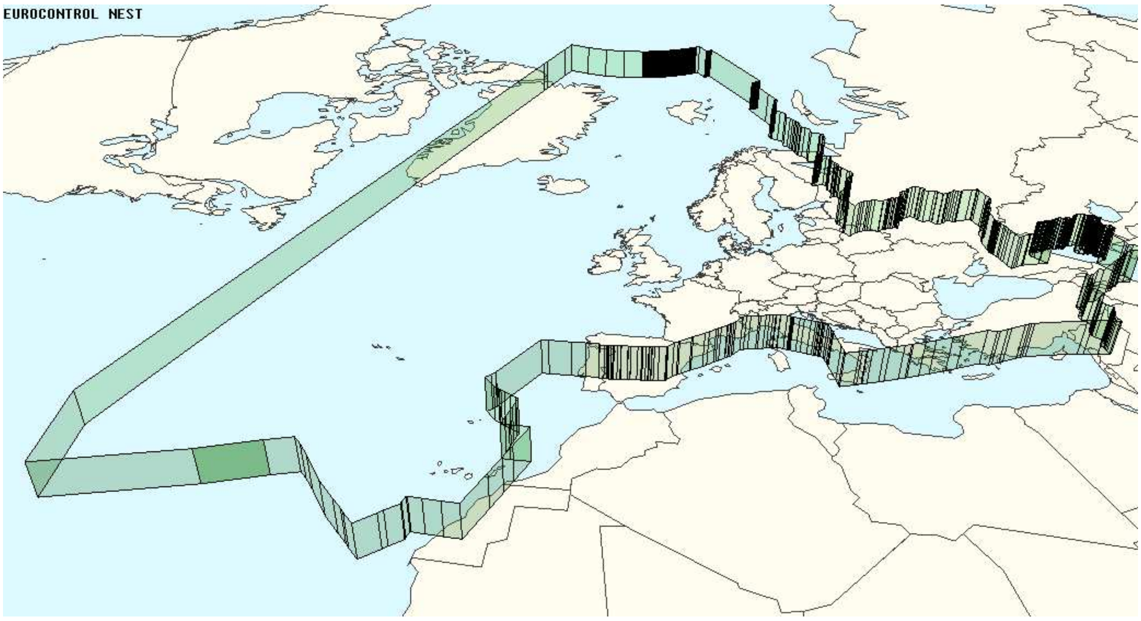

Figure 6.1 EUROFRA 3D overview

As commented in chapter three, new intermediate fixes need to be defined for the rest of the EUROFRA area. This was accomplished using a uniform waypoint network of 2600 intermediate fixes. The points were all located a degree apart in latitude and two degrees apart in longitude, with the worst case resulting in a distance of roughly 60 NM.

With this configuration, the segments of a flight plan defined over this grid will always remain below the 200 NM limit set by the ICAO (ICAO, Doc. 4444 AIr Traffic Management, 2016) for the maximum distance of a leg.

Figure 6.2 presents the border design (Entry/Exit) fixes and the intermediate fixes for the designed EUROFRA:

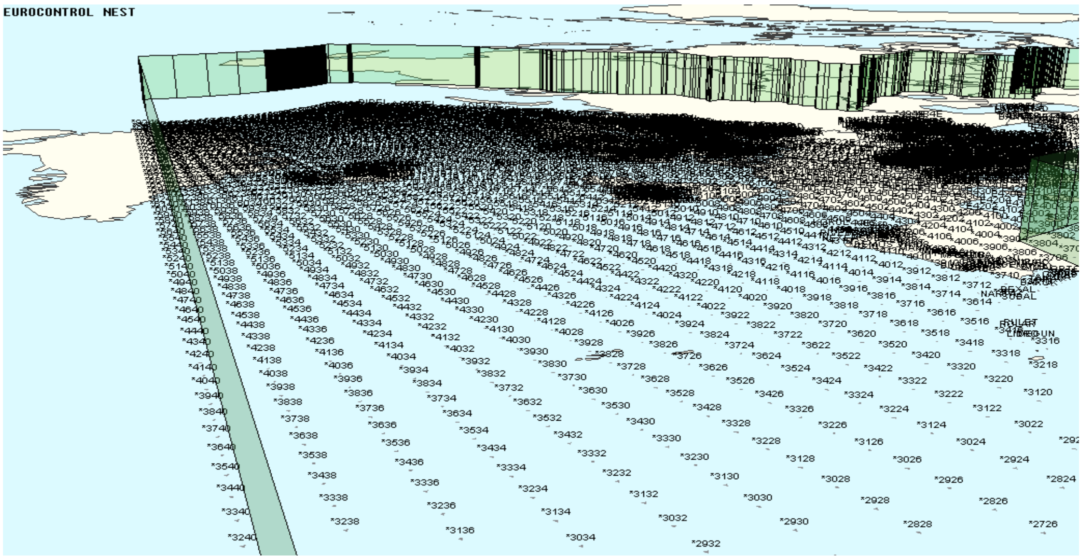

Figure 6.2 EUROFRA waypoint configuration

6.2. EUROFRA Evaluation

As evaluated in previous scenarios, some points were defined. In this case, for the Eastern segment of EUROFRA, as the current airspace is already well defined, FRA entry and exit points were directly obtained from Eurocontrol (Eurocontrol, Demand Data Repository, 2019).

In regions where FRA was not available, some points needed to be created, generating an intermediate network as presented in Figure 6.2. In the case of arrival/departure points, they should relate to the corresponding SID and STAR in use today.

For simplicity reasons, the sectorisation used in this scenario remains the same as in NEFRA, but considering all European ACCs, this sectorisation corresponds to AIRAC 1707.

Finally, it is important to note that all flights that crossed EUROFRA have been considered for the evaluation, representing an increase of 10 to 20 times compared to previous evaluations.

6.3. EUROFRA Results

Like previous chapters, EUROFRA results are synthesised into several figures and graphics, where it is important to note the following aspects:

- Green bars and lines correspond to the difference between free route and initial values or not free route.
- Blue bars correspond to initial values.
- Orange bars and lines relate to the mean of presented values.

- For simplicity, a difference between free route and initial traffic is presented in percentage (%).

6.3.1. EUROFRA Traffic Characterisation

Traffic for the EUROFRA scenario was extracted from AIRACs and dates similar to those used in NEFRA and SW FAB. However, EUROFRA traffic drastically increases the number of flights, because it represents all the flights crossing the ECAC area (European airspace) per day.

Figure 6.3 presents the number of flights extracted from 2012, where the mean of the number of flights approximated 19.900:

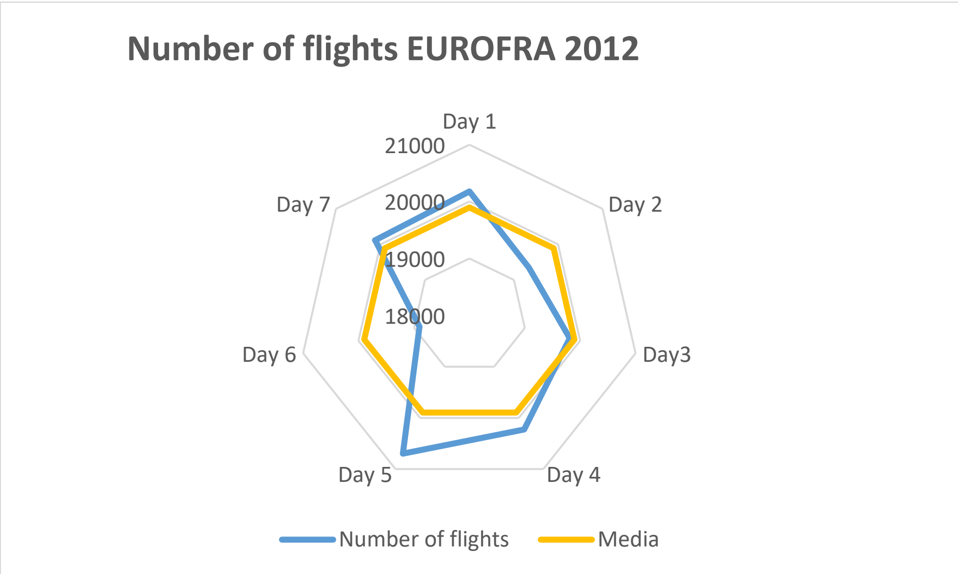

Figure 6.3 EUROFRA number of flights in 2012

Regarding flight distance from 2012 traffic samples, the mean of the initial flight distance values are approximately 24,696 million NM, related to the 19.900 flights previously mentioned.

Figure 6.4 depicts the distance flown by each traffic sample extracted from the demand data repository from Eurocontrol:

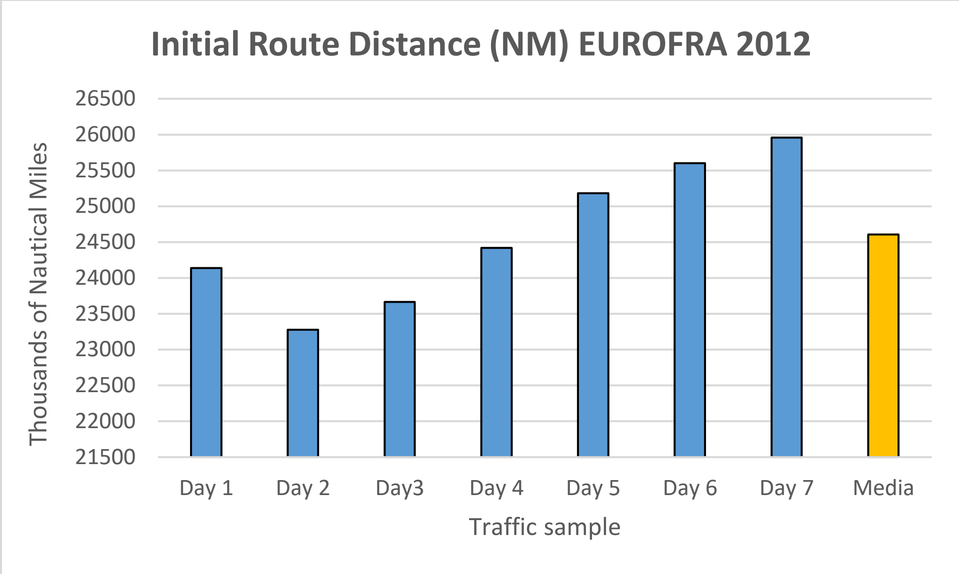

Figure 6.4 EUROFRA initial route distance in 2012

The next evaluation corresponds to the free-route distance flown by the 2012 traffic sample, with peak days resembling those of the initial sample. As a reference number, the mean distance equalled 24,344 million NM (see Figure 6.5).

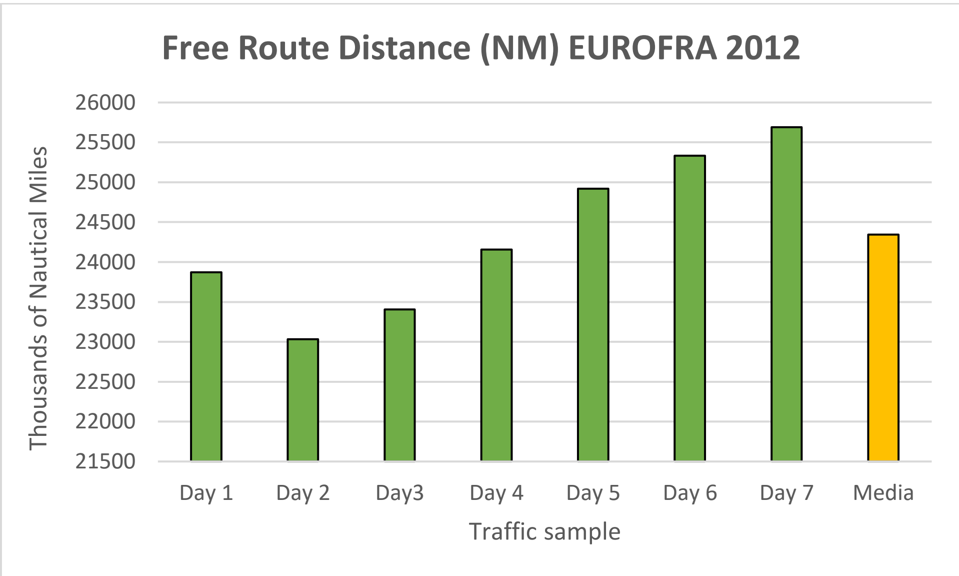

Figure 6.5 EUROFRA free-route distance in 2012

Concerning traffic data from 2018, the flight mean exhibits an increase of 5.000 flights per day compared to initial data from 2012, achieving a mean of 24.900 flights.

As described in Figure 6.6, the mean used for evaluation enables compensating for the differences between the highest or lowest flight number days.

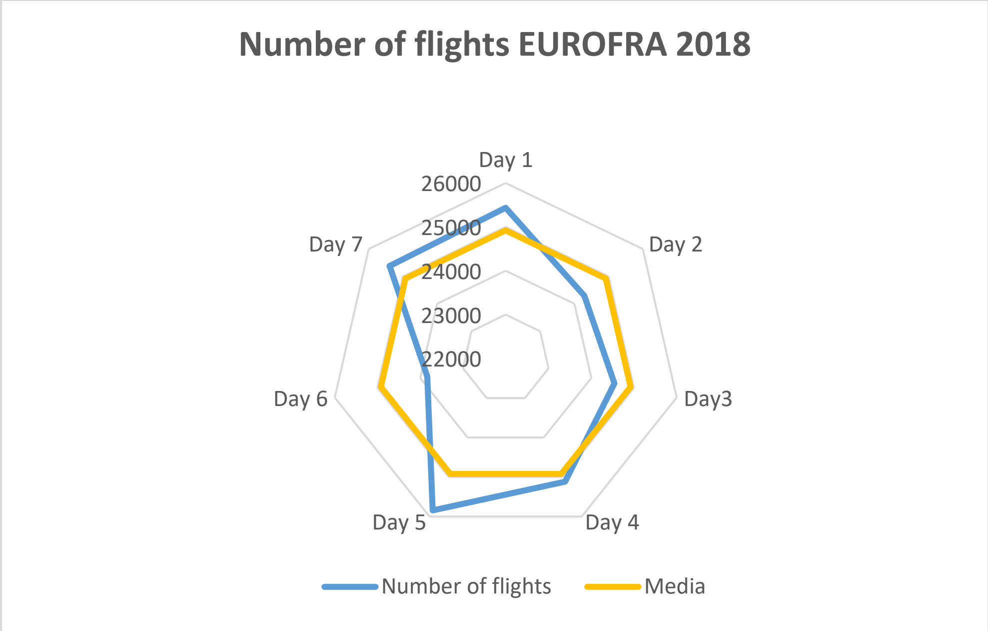

Figure 6.6 EUROFRA number of flights in 2018

Because of the increase of flights, the flight distance measured for the initial and free-route trajectories have increased.

In Figure 6.7, the mean of the initial distance increased to 8 million NM compared to traffic from 2012. Now, the 2018 mean equals approximately 32,077 million NM.

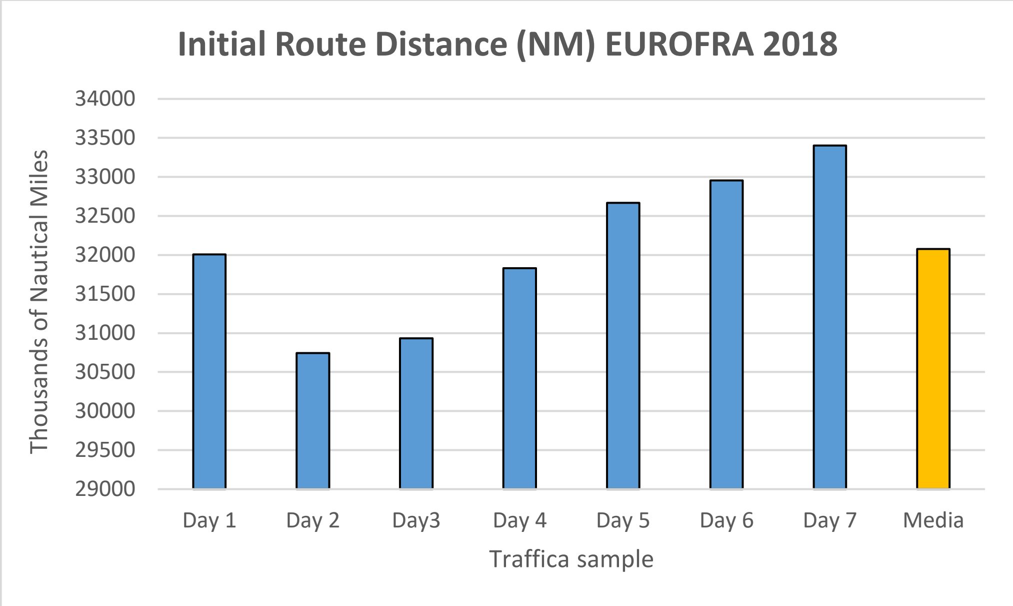

Figure 6.7 EUROFRA initial route distance in 2018

Meanwhile, free-route distance exhibits a mean distance of 31,687 million NM and demonstrates the same peaks days as initial traffic. The values are presented in Figure 6.8:

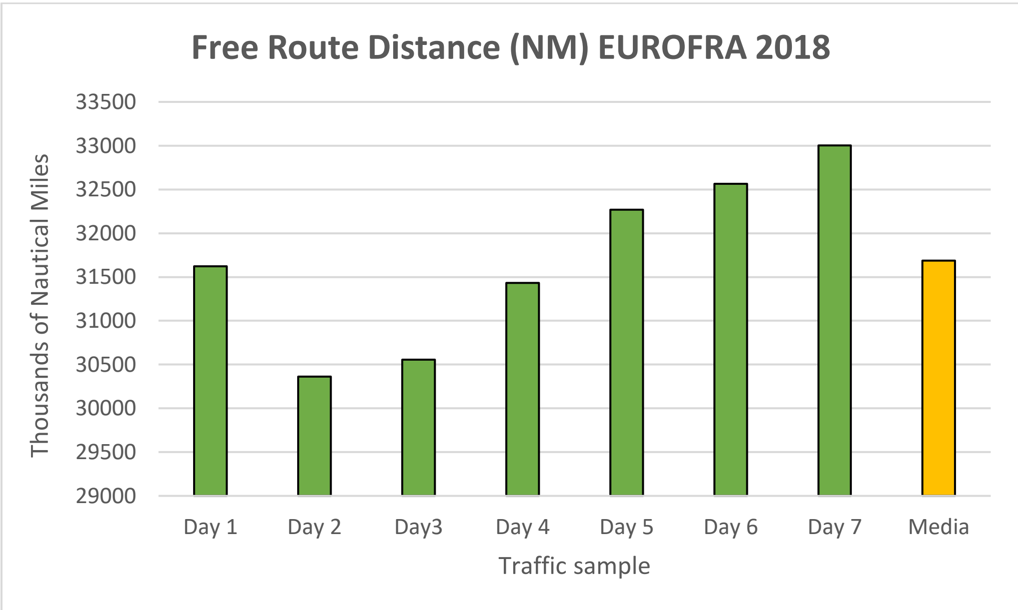

Figure 6.8 EUROFRA free-route distance in 2018

Regarding traffic samples from 2024, the traffic prognosis estimates 31.721 flights as the mean value, approximately 7.000 more flights for the ECAC area.

The initial values for the number of flights for 2024 are described in Figure 6.9:

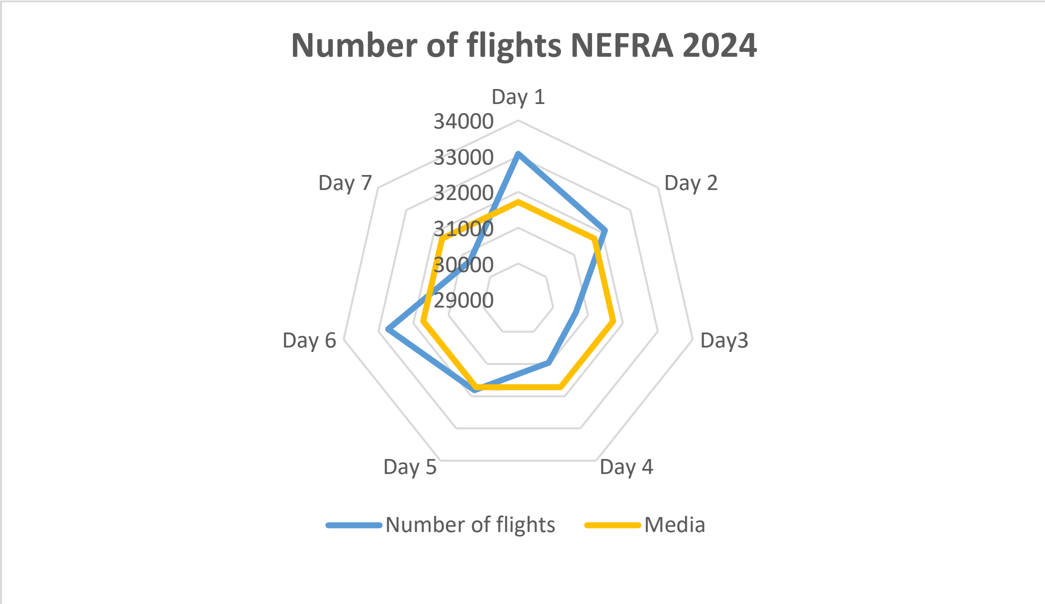

Figure 6.9 EUROFRA number of flights in 2024

Regarding flight distance, the measures indicate another 8 million NM more for the initial traffic samples, with a mean distance value of 42,016 million NM (see Figure 6.10).

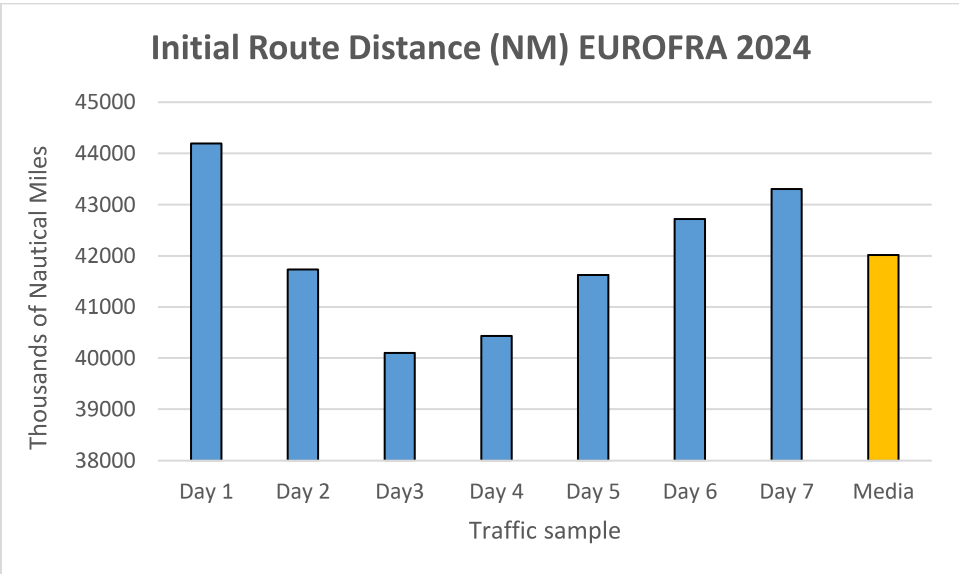

Figure 6.10 EUROFRA initial route distance in 2024

In the same way, Figure 6.10 illustrates an increase in the free-route distance for 2024, reaching a mean value of 41,469 million NM per day.

As can be seen in Figure 6.11, the peak days exhibit similarities to the initial samples:

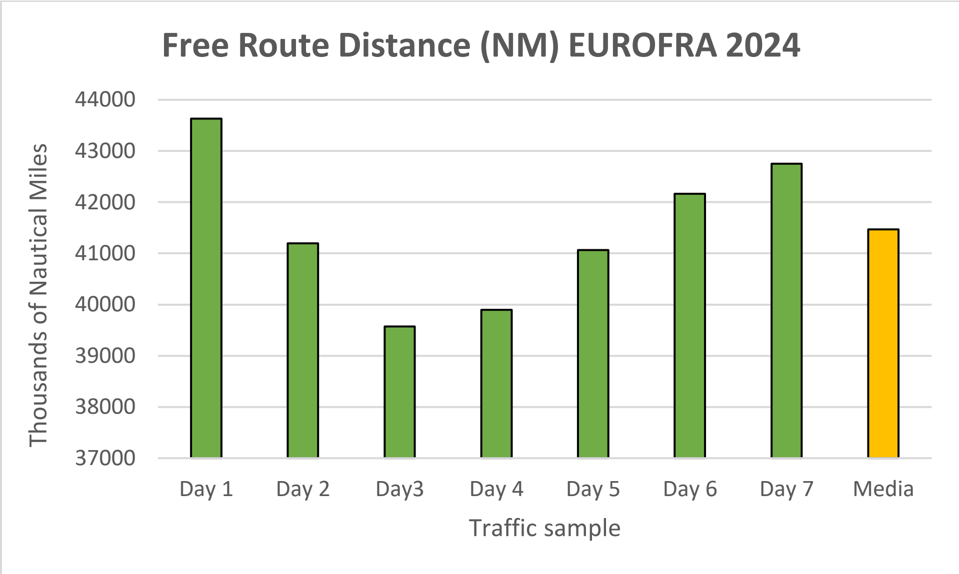

Figure 6.11 EUROFRA free-route distance in 2024

The traffic samples presented in the EUROFRA area (see Figure 6.11) offer an estimation using the prognosis algorithm FIPS from Eurocontrol and described in the previous chapter.

Nevertheless, if we compare the European traffic from 2012 and the traffic from 2024, the number of estimated flights demonstrate an increase of around 60% in only 12 years. These macroscopic values are employed as a starting point to support free-route implementation. The next sections of the study consider the mean values.

6.3.2. EUROFRA Distance Saving Results

As demonstrated in the next table, the results indicate that free-route implementation in the EUROFRA area presents benefits in terms of distance savings for airspace users. In general, distance savings vary from 1,06 to 1,30% of the total distance. Table 6.1 details the values resulting from the simulations and considers the mean value from each year:

Table 6.1 EUROFRA distance savings

Measure	2012	2018	2024
Initial route distance (NM)	24606211,6	32077218,1	42016458,1
Free-route distance (NM)	24344324,9	31687396,0	41469022,8
Distance savings (NM)	261886,7	389822,1	547435,2

According to Table 6.1, the absolute values of distance savings with EUROFRA implementation range between 262 and 547 thousand NM per day.

The presented values directly relate to the optimisation of preferred routes with free route. Furthermore, this approach is based on the simulation inputs. Nevertheless, results remain highly favourable for free route, supporting the concept explained in paragraph 2.4, where free route gains are elaborated.

Figure 6.12 represents the values described in the last table, where it is easy to identify the distance saving tendency as the traffic sample scenario changes.

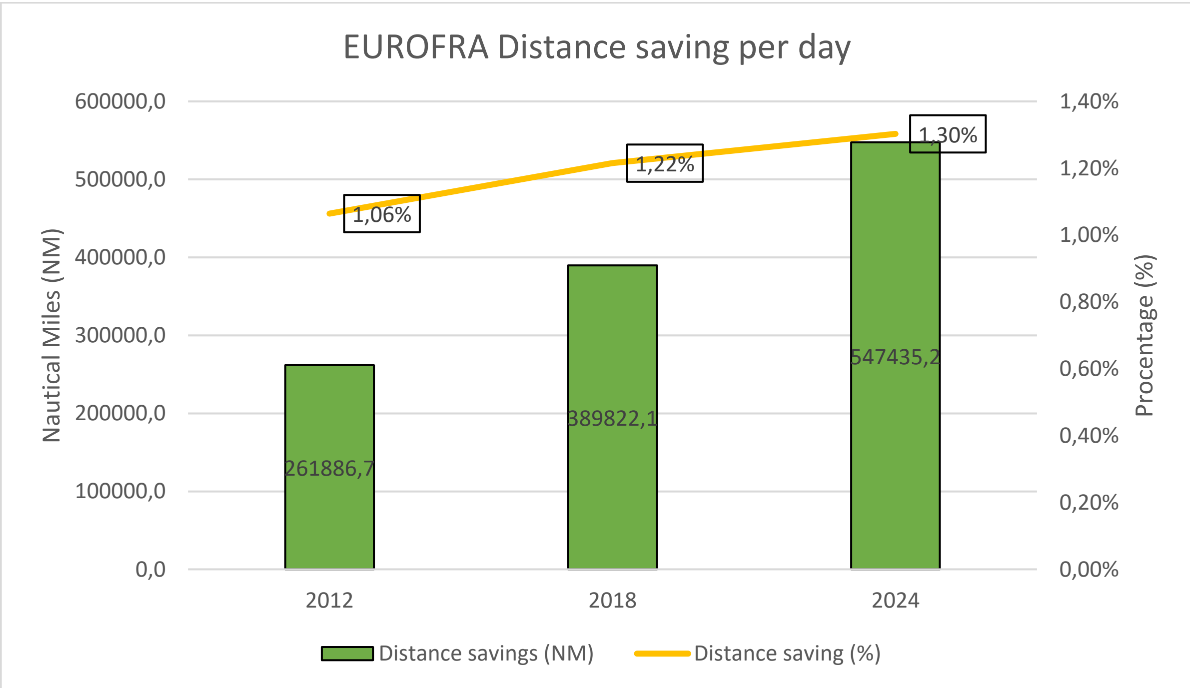

Figure 6.12 EUROFRA distance savings

From Figure 6.12, the most notable result concerns the volume of NM saved with full free-route implementation, exceeding 0,5 million NM.

These results are consistent with those of other studies (De Herdt, 2018), (Henn, A., 2015) (Eurocontrol, 2011) (Button & Neiva, 2013). Additionally, this suggests that airspace benefits for users increase as fewer constraints are imposed, such as structural, time and flow restrictions.

6.3.3. EUROFRA Flight Time Saving Results

The study of flight time related to traffics simulated in the EUROFRA environment is summarised in the next table, where the absolute values of flight time savings in minutes and hours are presented.

In Table 6.2, it is easy to note that flight time savings are demonstrated and growing as the traffic volume increases, estimating 42h for 2024 traffic samples and representing 30% more than the 2018 estimation.

Table 6.2 EUROFRA flight time savings

Measure	2012	2018	2024
Flight time savings (h)	23,0	30,3	42,2
Initial flight time (h)	952,6	1236,9	1617,9
Free route flight time (h)	929,6	1206,6	1575,7

Figure 6.13 depicts the absolute flight time savings represented in flight hours to simplify their understanding.

From the figure, and similarly to distance savings, it can be stated that, as more traffic loads utilise a full FRA, more benefits are expected in terms of flight time savings.

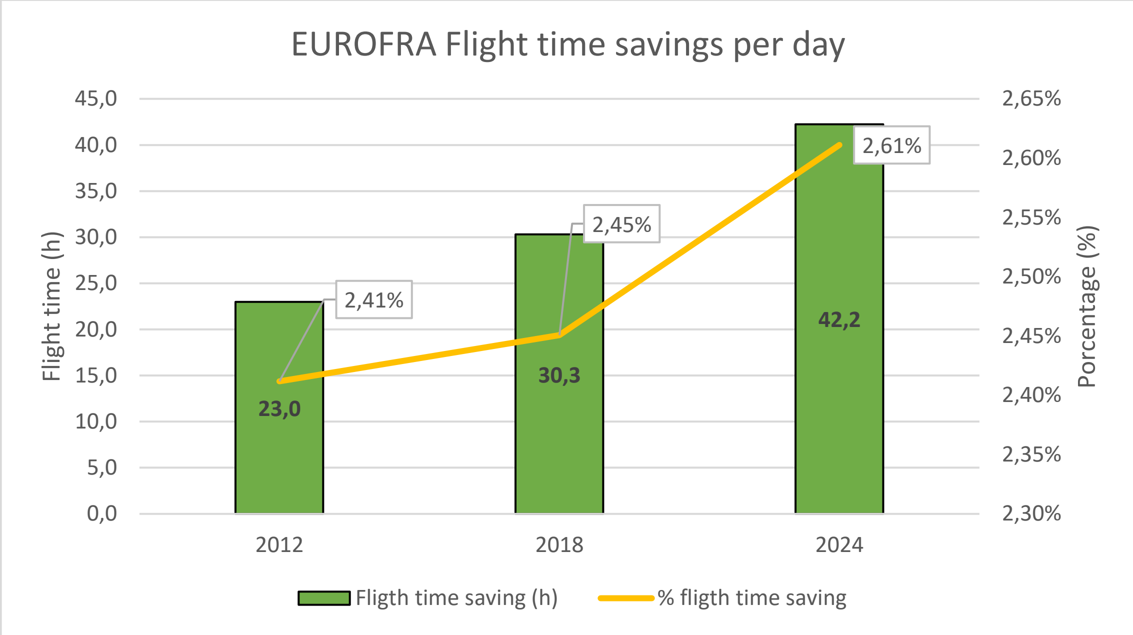

Figure 6.13 EUROFRA flight time savings

This finding confirms the association between flight time saving, fuel and emission savings.

Considering the relation of flight time, fuel consumption and emission from Eurocontrol (Eurocontrol, NEST User Manual, Version 1.6, 2018), the next relations presented in Table 6.3 could be extrapolated to EUROFRA results.

Table 6.3 EUROFRA fuel and emissions savings

Measure	2012	2018	2024
Flight time saving (h)	23,0	30,3	42,2
Fuel saving (tons)	46,0	60,8	84,7
CO2 emissions (tons)	144,6	190,8	265,9
NOx emissions (tons)	0,4	0,5	0,7

Figure 6.14 presents the macroscopic values concerning flight time savings. This also accords with earlier observations, which demonstrated important benefits if a full free-route concept is applied.

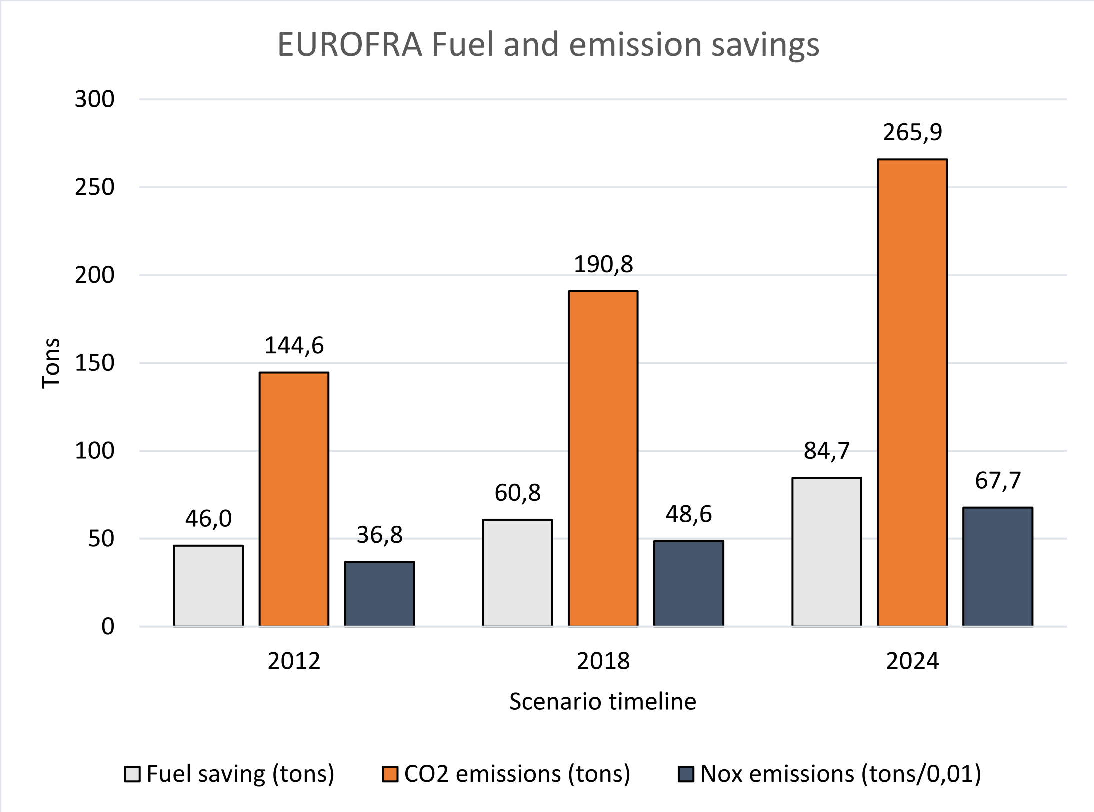

Figure 6.14 EUROFRA free-route fuel and emission savings

As summarised, simulations demonstrated that, considering a futurist scenario with full free-route implementation across Europe, benefits for airspace users are clearly demonstrated.

For approximately 32.00 flights in 2024, distance saving equal roughly 550.000 NM per day. In addition, flight time savings approximate 42 flight hours, which translates into savings of 84 fuel tons and 266 CO_2 tons per day.

6.3.4. EUROFRA Conflict Results

The conflict analysis in the EUROFRA scenario demonstrates a high increase in number compared to other scenarios from NEFRA and SW FAB.

As illustrated in Figure 6.15, where the difference between initial and full free route is represented, the favourable results in difference (%) indicate that EUROFRA reduces conflicts from 11 to 17% as the traffic load increases, according to the scenarios.

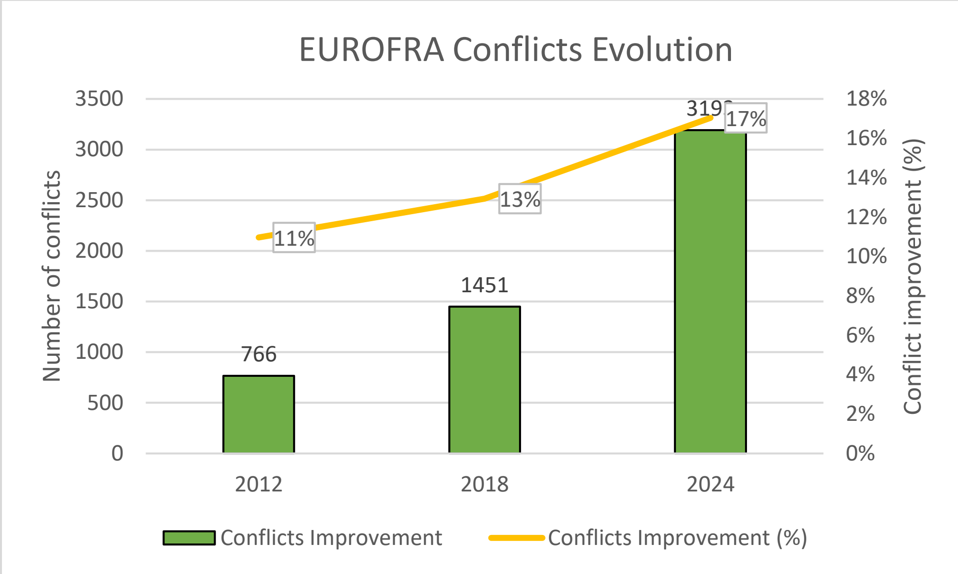

Figure 6.15 EUROFRA conflict evolution

Like previous results for NEFRA and SW FAB, traffic dispersion reduces the conflicting trajectories and measures.

Although all these results present a favourable predisposition in reducing the number of conflicts, this does not mean that complexity will be reduced, as these comprise independent indicators.

6.3.4.1. Detailed conflict scenario EUROFRA 2012

A detailed analysis of the total conflicts from the 2012 scenario is accordingly presented in the following figures.

Figure 6.16 in particular illustrates a simple statistical analysis to demonstrate that conflicts reduce by 8 to 15% using a full free-route scenario.

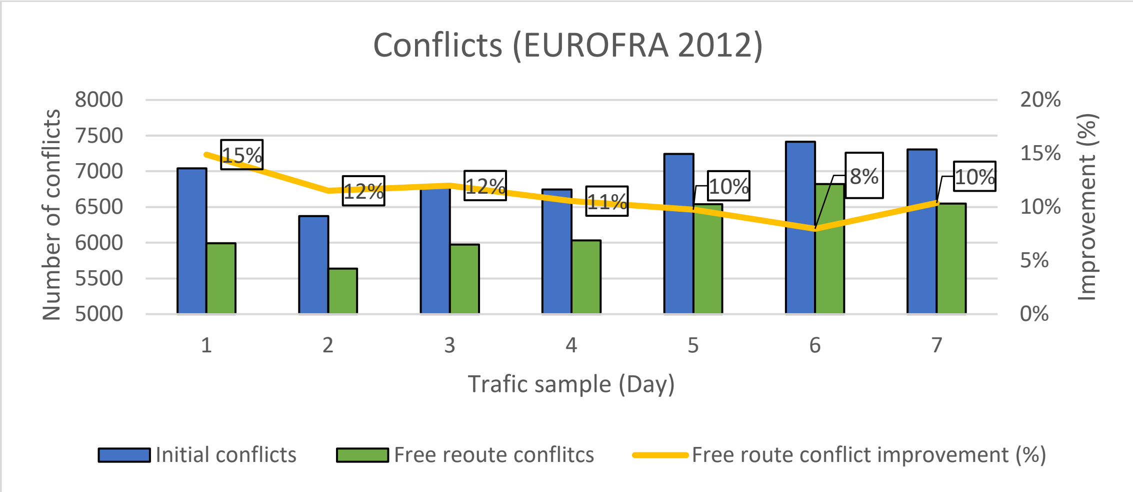

Figure 6.16 EUROFRA conflicts per day in 2012

In the vertical dimension (see Figure 6.17), results are categorised for trajectories status or flight evolution. In this sense, it easy to note that conflicts in evolving/cruise have decreased by approximately 8%. Furthermore, conflicts in cruise/cruise trajectories reach an improvement of 8%. This last result is correlated with the horizontal increases.

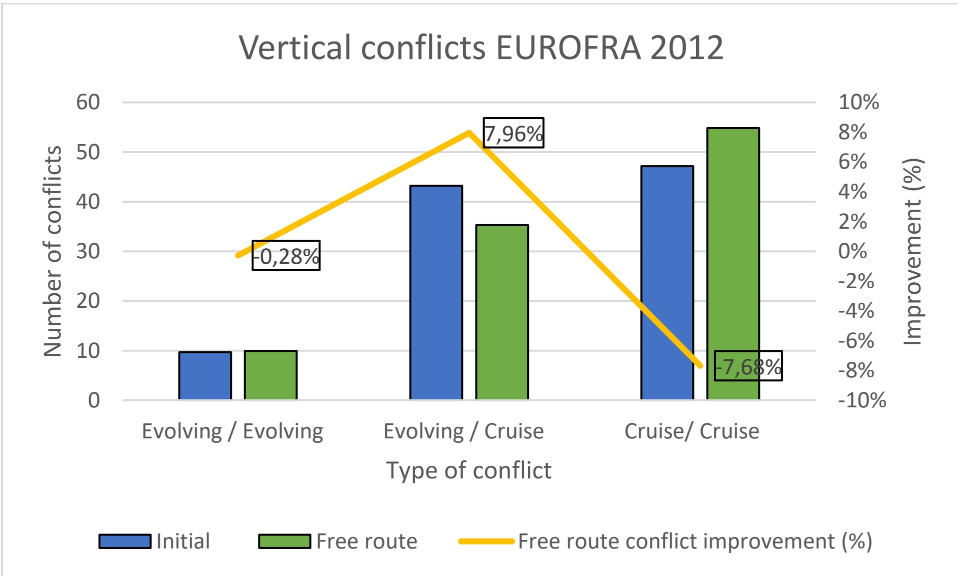

Figure 6.17 EUROFRA vertical conflicts in 2012

Regarding horizontal conflicts, as described in Figure 6.18, free-routed traffic from 2012 exhibits approximately 38% more conflicts relative to crossing trajectories—a high increase. On the other hand, the conflicts from parallel traffic are reduced by 43%.

In general, the results described in the horizontal dimension were expected for EUROFRA because, with the use of preferred trajectories, flight trajectories tend to be less parallel (not using airways) and manage to fly more direct routes using entry and exit waypoints, in turn drastically increasing the crossings.

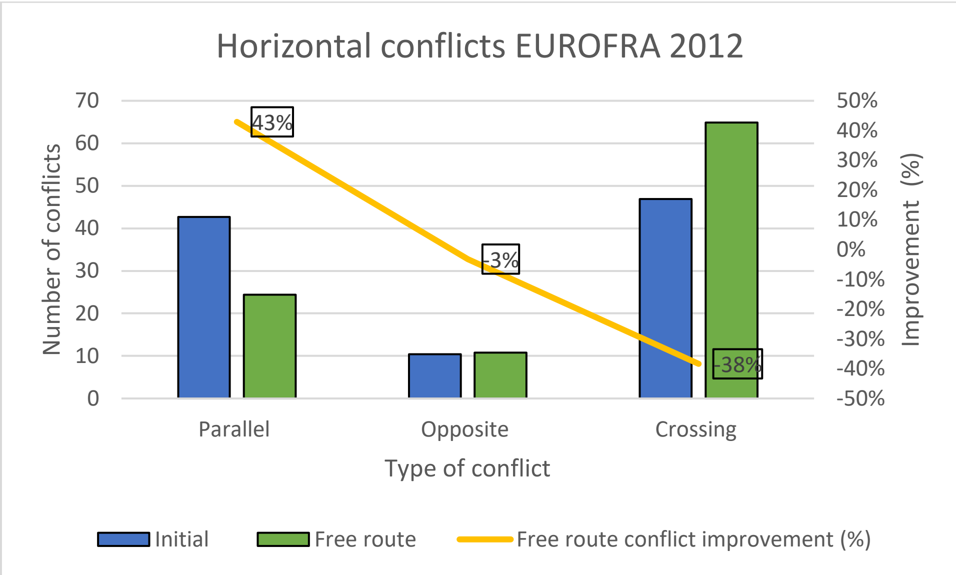

Figure 6.18 EUROFRA horizontal conflicts in 2012

A detailed analysis of each type of conflict with 2012 traffic is presented in Figure 6.19.

Similar to previous results, cruise/cruise/crossing trajectories increased by 54% and represent more than 40% of the global conflicts in free route. These results are supported by previous results in vertical and horizontal dimensions.

Another notable result concerns the reduction in vertical conflicts, all related to evolving/cruise/parallel, which reduced by 46% and represent approximately 20% of the total conflicts before free route.

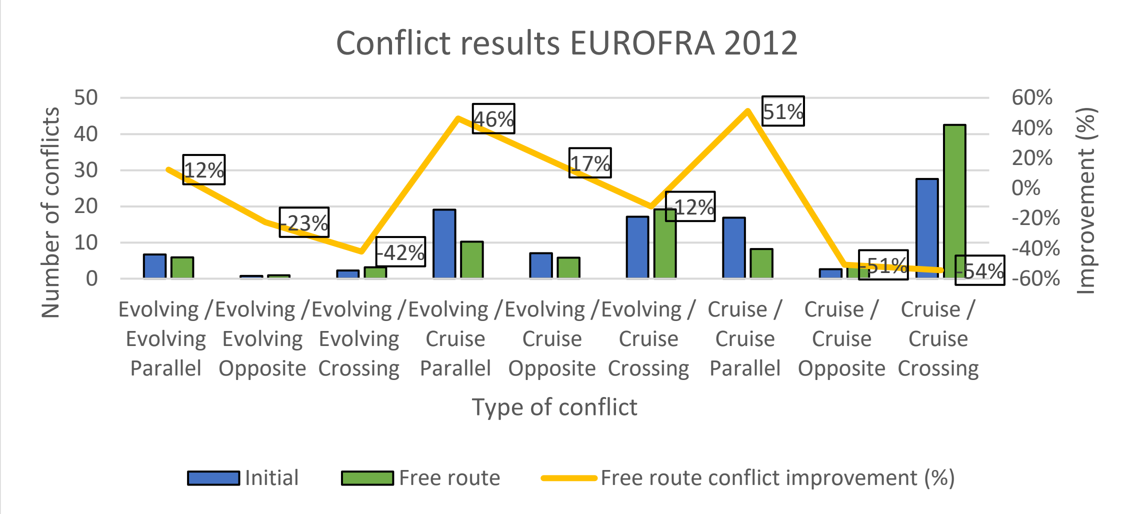

Figure 6.19 EUROFRA conflict results in 2012

6.3.4.2. Detailed conflict scenario EUROFRA 2018

From 2018 traffic samples, results demonstrate a considerable decrease in the number of conflicts, dropping from approximately 10 to 15% in all the sample (see Figure 6.20). This reduction in conflicts is distributed and studied in the following figures.

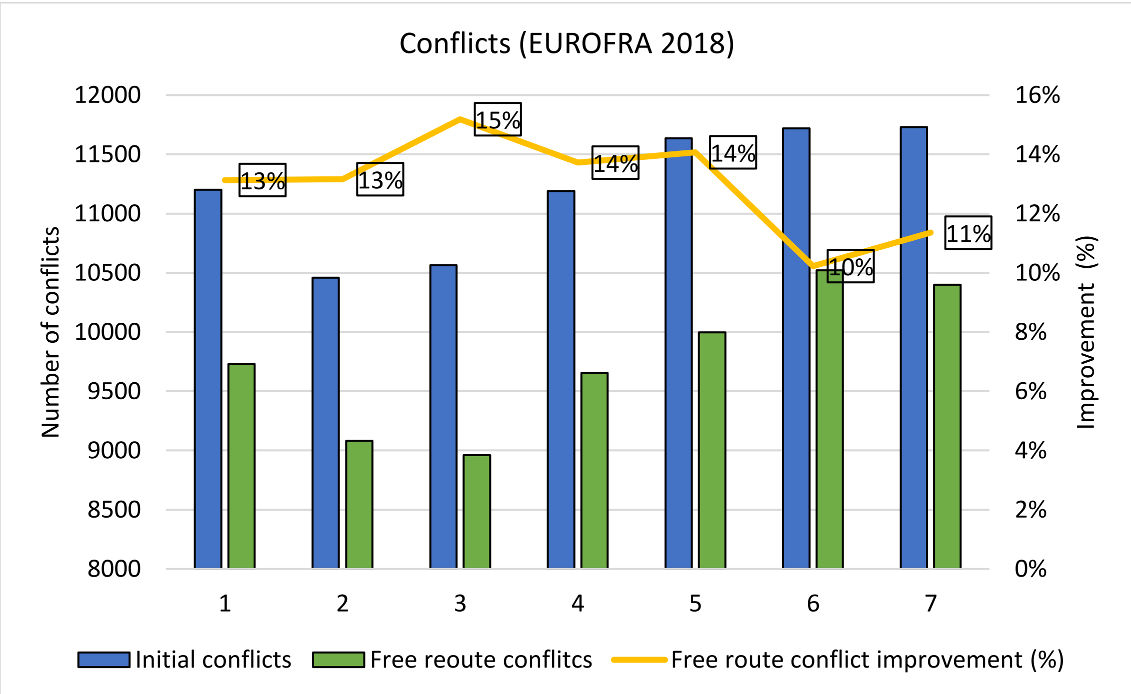

Figure 6.20 EUROFRA conflicts in 2018

For the vertical dimension conflicts presented in Figure 6.21, simulations demonstrate that the cruise/cruise conflicts represent approximately 50% of the conflicts. Consequently, an increase of 21% for this type of conflict will affect trajectories.

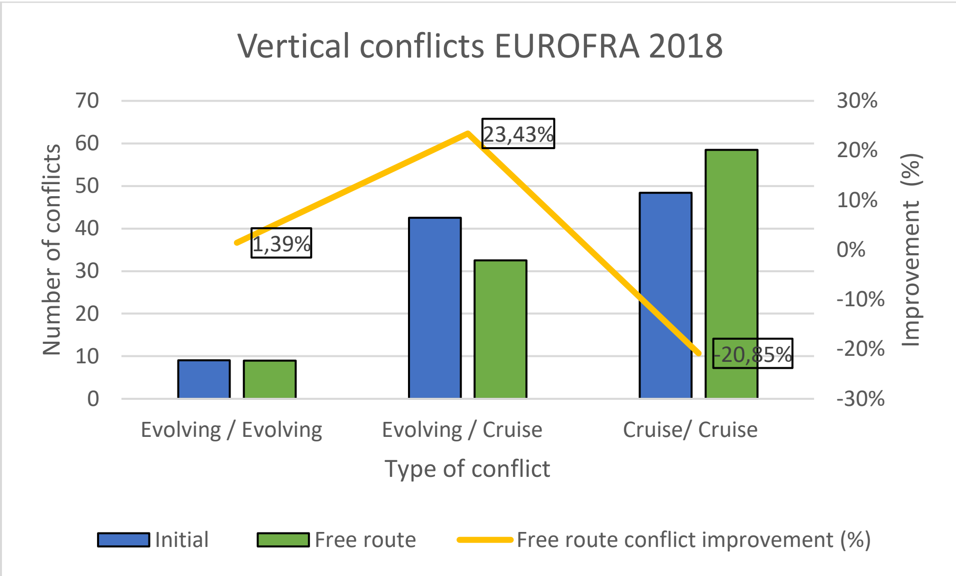

Figure 6.21 EUROFRA vertical conflicts in 2018

Another important result concerns vertical conflicts from 2018. Specifically, evolving/cruise conflicts were reduced by 23%, representing approximately 30% of the sample in free route.

For the horizontal dimension, results from Figure 6.22 confirm that crossing conflicts, which represented approximately 50% of the sample before free route, were increased by 42%, comprising the most weighed type in the horizontal dimension.

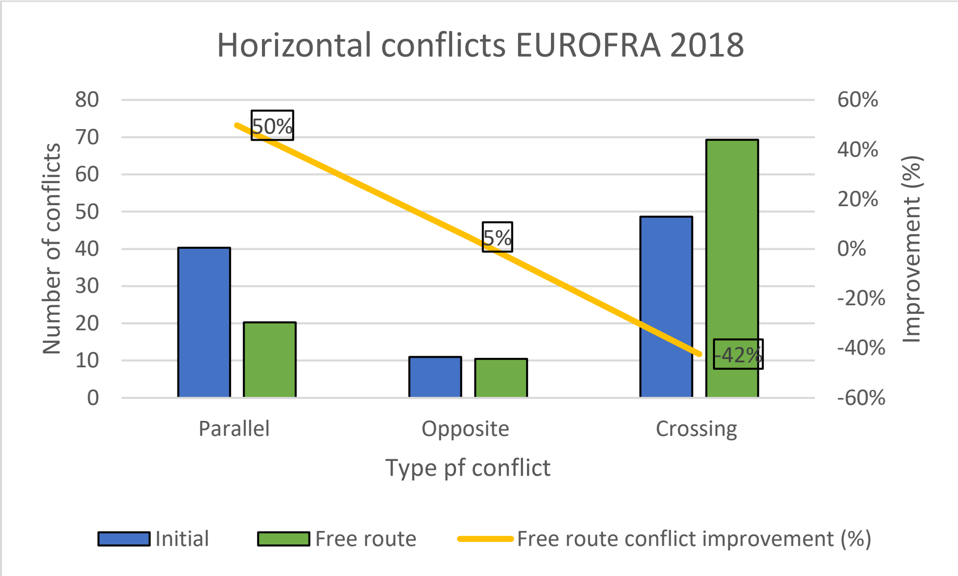

Figure 6.22 EUROFRA horizontal conflicts in 2018

The general overview of conflict results in 2018 presented in Figure 6.23 reaffirms previous results described in this section, where increases in conflicts in the horizontal dimensions are demonstrated with free-route implementation.

As illustrated in Figure 6.23, the most notorious increase relates to cruise/cruise/crossing conflicts, passing from 30% to more than 45% of the total number of conflicts. Specifically, it experiences an increase of 62% with EUROFRA application.

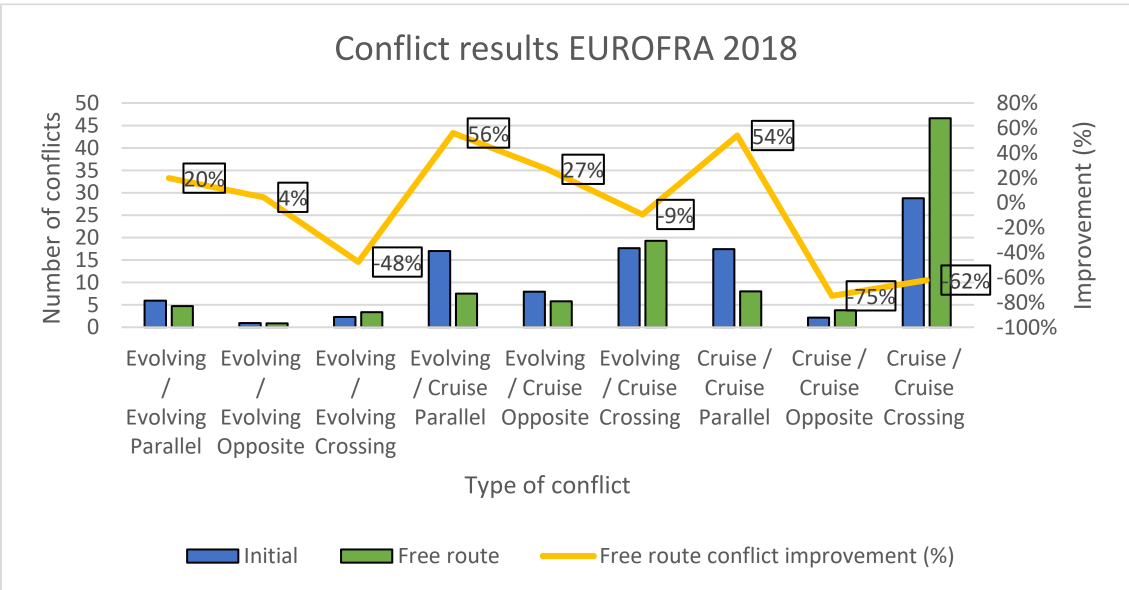

Figure 6.23 EUROFRA conflict results in 2018

Related to the evolving conflicts, free-route implementation generally indicates more favourable results, especially in the evolving/cruise/parallel trajectories (see Figure 6.23).

6.3.4.3. Detailed conflict scenario EUROFRA 2024

From the 2024 scenario, reductions similar to those from previous traffic were registered. Simulations demonstrated that the mean per day was reduced between 15 to 19%. This slight increase compared to 2018 and 2012 is supported by the increase in the number of flights, which directly relates to the number of conflicts.

Figure 6.24 presents the number of conflicts per day according to simulations with traffic samples from 2024:

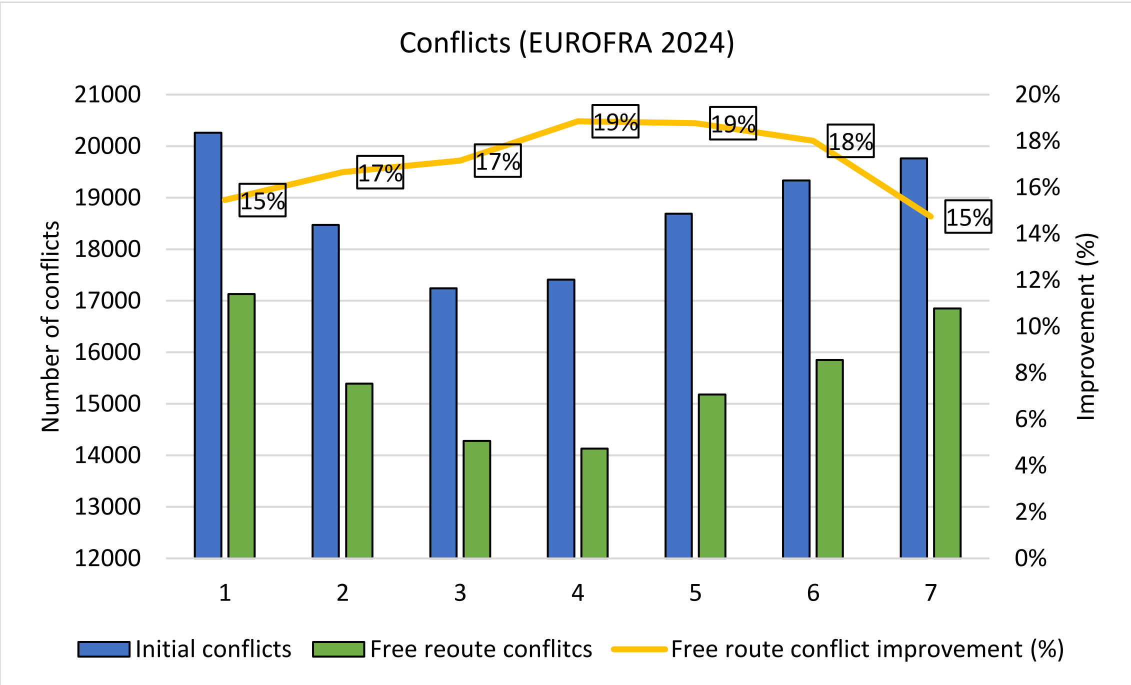

Figure 6.24 EUROFRA conflicts in 2024

The vertical conflicts described in Figure 6.25 indicate that cruise/cruise trajectories are the most conflicting, representing approximately 50% of the total conflicts in vertical and experiencing an increase of 16,7% after free route.

The evolving/cruise traffic decrease of approximately 22% is detailed in the next figure:

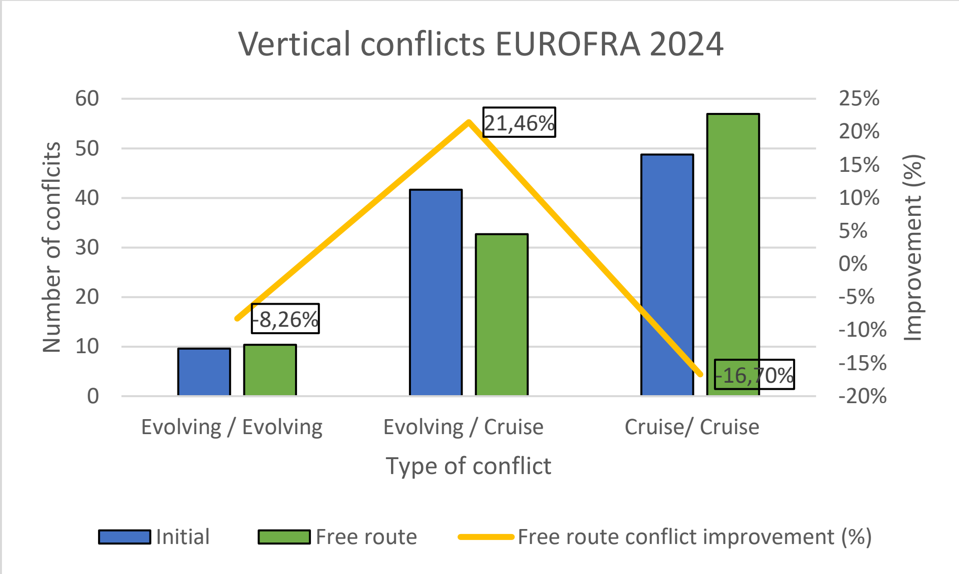

Figure 6.25 EUROFRA vertical conflicts in 2024

The study of horizontal conflicts represented in Figure 6.26 using traffic from 2024 indicates that the crossing trajectories are increased. This notable increase of 46% compared to the scenario without full free route indicates that trajectories are becoming more disperse and random. However, the complexity of these effects are studied further in the next section.

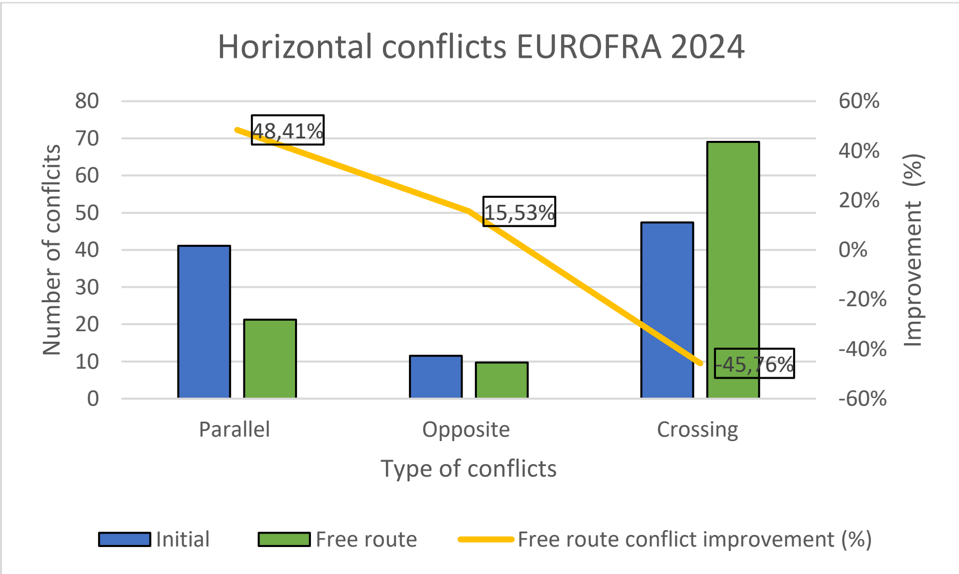

Figure 6.26 EUROFRA horizontal conflicts in 2024

The general distribution of conflicts from 2024 presented in Figure 6.27 demonstrate that, with a full FRA in Europe, the cruise/cruise/crossing conflicts will be drastically increased by 61%.

Conversely, simulation results demonstrate some improvements in vertical conflict evolution, reducing evolving/cruise/parallel conflicts by 57%, representing more than 15% of the total before free-route simulations.

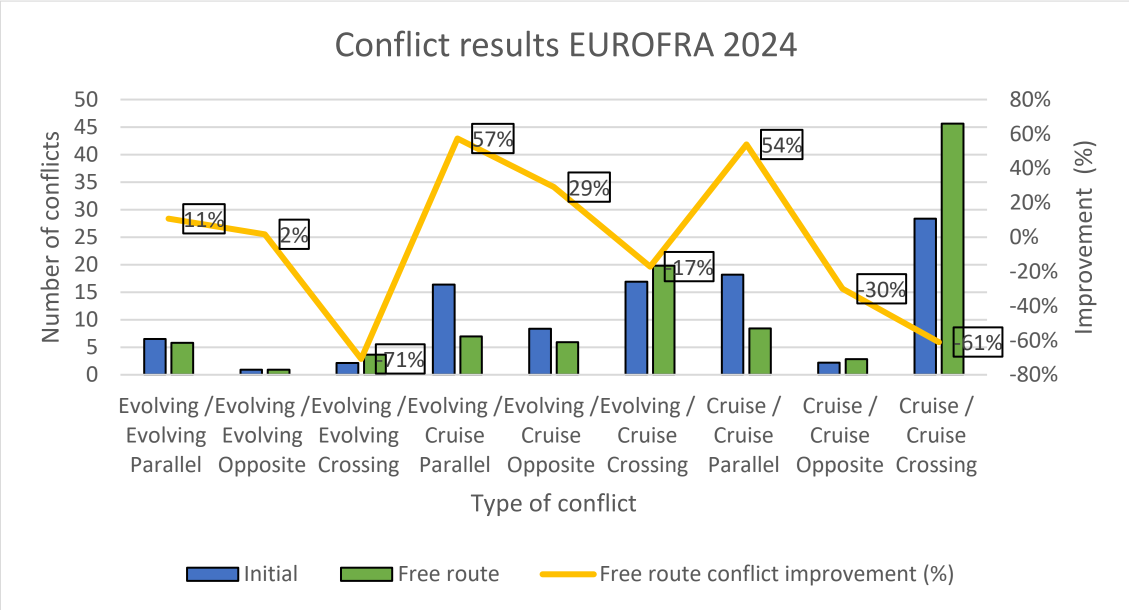

Figure 6.27 EUROFRA conflict results in 2024

In general, EUROFRA conflict results indicate increases in the horizontal conflicts, largely related to crossing trajectories in cruise status (see Figure 6.27).

On the other hand, this remains contrary to the vertical dimensions, where simulation results demonstrated that, with free route, traffic tends to be more stratified, reducing evolving interactions.

The conflict indicator, as previously described in this thesis, offers a measure for studying how conflicting traffic is following airspace changes.

Nonetheless, conflict results support the specific analysis of complexity, presented in the next section for EUROFRA airspace implementation.

6.3.5. EUROFRA Complexity Results

The complexity study of EUROFRA airspace is presented much like previous complexity sections. First, results from adjusted density by each scenario are discussed, followed by global results. After this, the results for vertical, horizontal and speed interactions are depicted. Then, structural index analysis and the complexity score values are detailed.

Results were condensed by years (2012, 2018 and 2024) for simplicity and better understanding.

6.3.5.1. EUROFRA Adjusted density

Figure 6.28 illustrates results for adjusted density regarding 2012 data. Here, it is easy to note that EUROFRA presents improvements approximating 25% compared to the compared airspace.

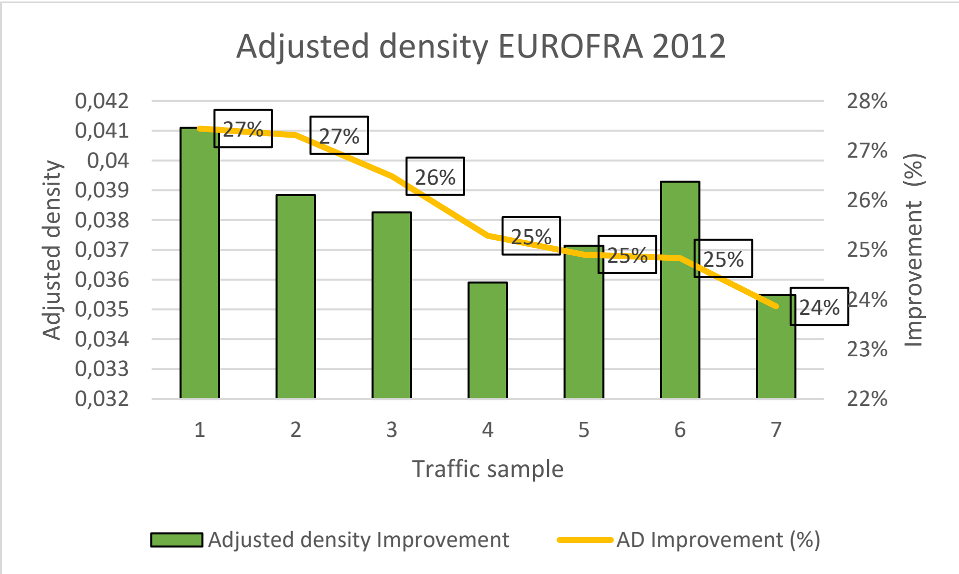

Figure 6.28 EUROFRA adjusted density in 2012

Similar values are registered in simulations from 2018, where all adjusted density results exhibit more favourable results compared to the previous airspace studied (see Figure 6.29).

The next figure provides the results of adjusted density for each day evaluated from 2018:

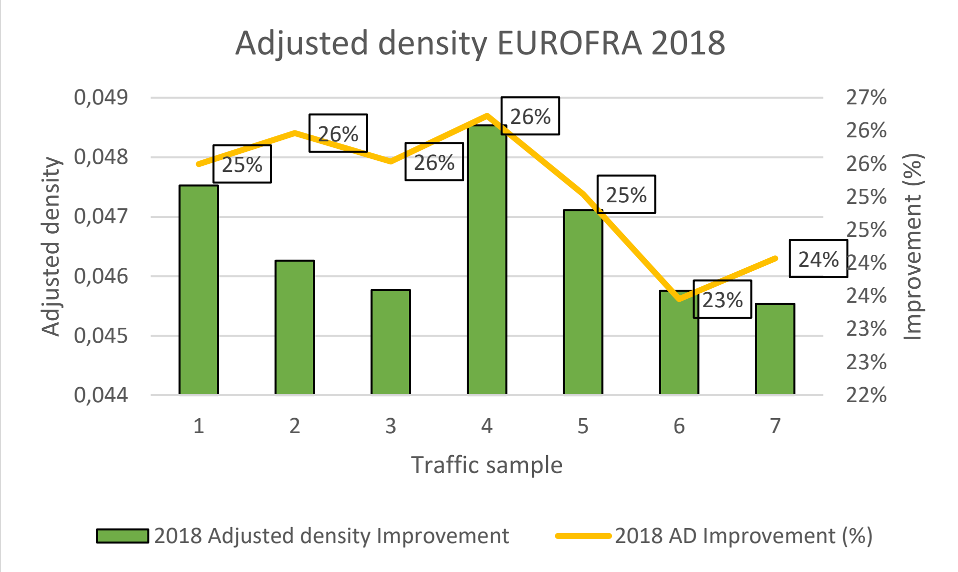

Figure 6.29 EUROFRA adjusted density in 2018

In the same line, results in Figure 6.30 from 2024 indicate a reduction of roughly 25% compared to the 2024 prognosis, even with the increased number of flights.

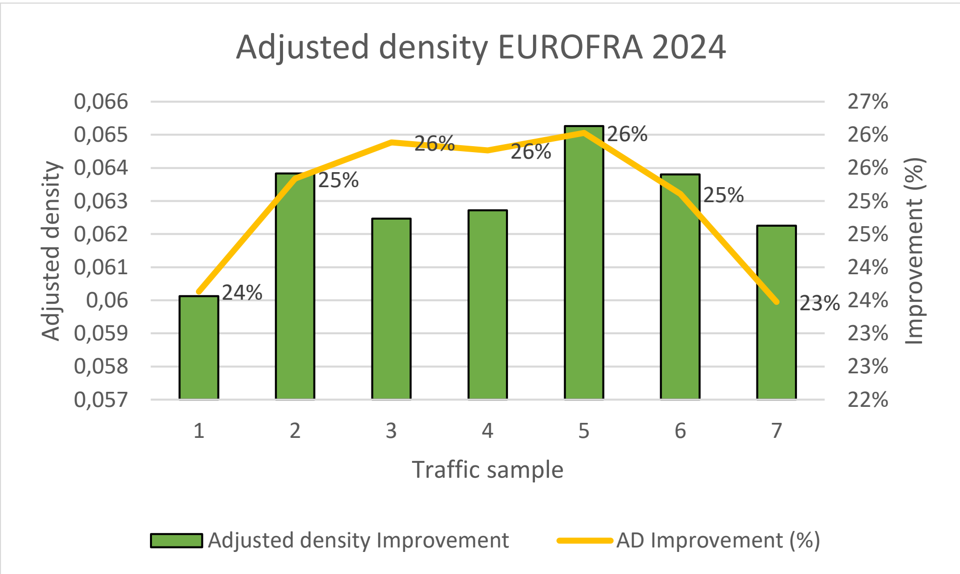

Figure 6.30 EUROFRA adjusted density in 2024

The overall results for adjusted density (see Figure 6.31) are presented in the next graphic, where the absolute value of adjusted density increases as more traffic loads are simulated.

As the adjusted density depends directly on controlled flight hours, it is expected to experience an increase of the values. What is interesting in this data is that the average reduction or improvement of adjusted reached 25% with all traffic samples, meaning that the interactions between evaluated airspaces are reduced with the free-route scenario.

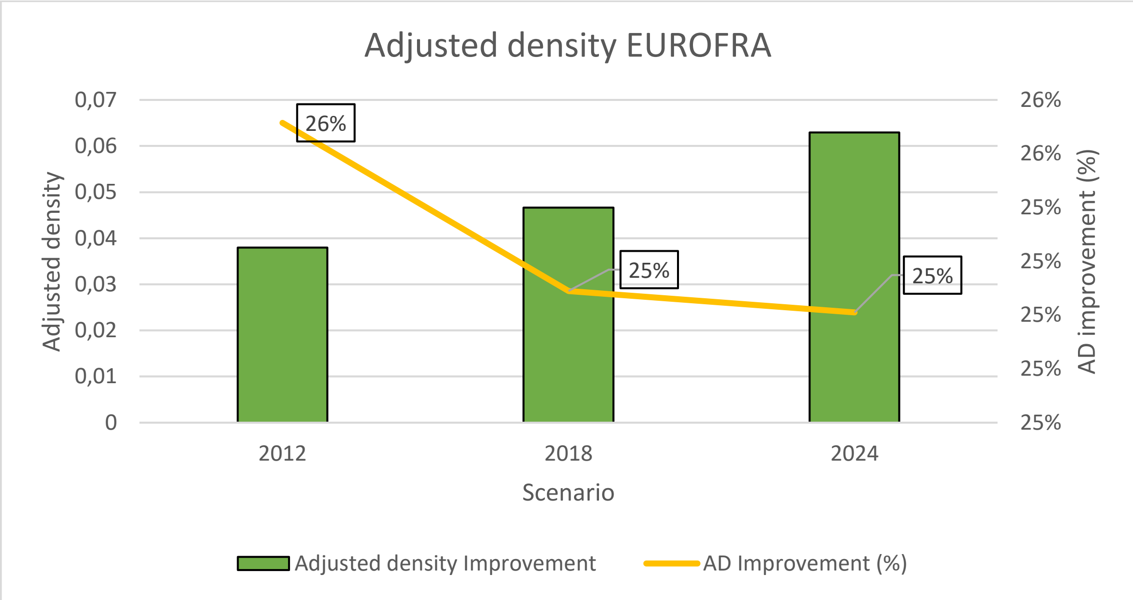

Figure 6.31 EUROFRA adjusted density

6.3.5.2. EUROFRA Complexity indicators

For the vertical dimension in Figure 6.32, complexity is reduced, resulting in an improvement between 34 and 39%, of the vertical interactions simulated.

Correlating these results with conflict results from section 6.3.4, where vertical conflicts regarding evolving traffic were reduced, it can be stated that free-route implementation drastically reduces vertical complexity.

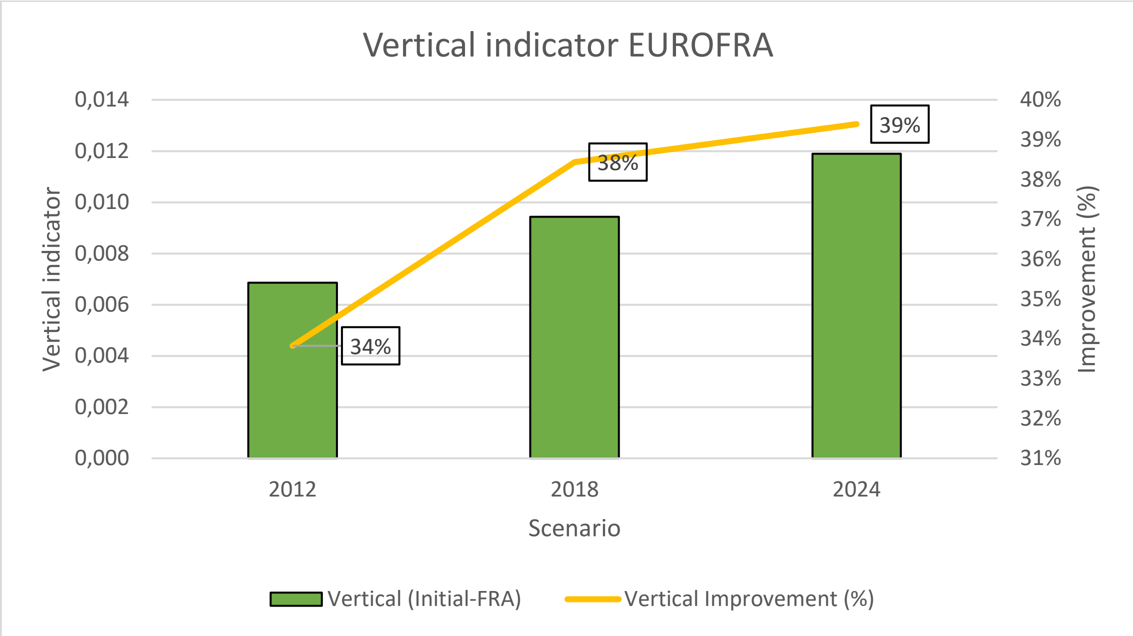

Figure 6.32 EUROFRA vertical indicator

For the horizontal indicator (Figure 6.33), results indicate a negative influence by free-route implementation, increasing the horizontal interactions values between 9 and 11%. These results contrast those identified in the conflict section (6.3.4), where findings indicated that crossing conflicts in cruise level status are the most penalised.

Results from horizontal interactions are supported by the free-route trajectories behaviour. This distribution is random, and crossings could be generated anyway, contrary to ATS airways airspace, where hot spots or conflicting points are expected in the crossings.

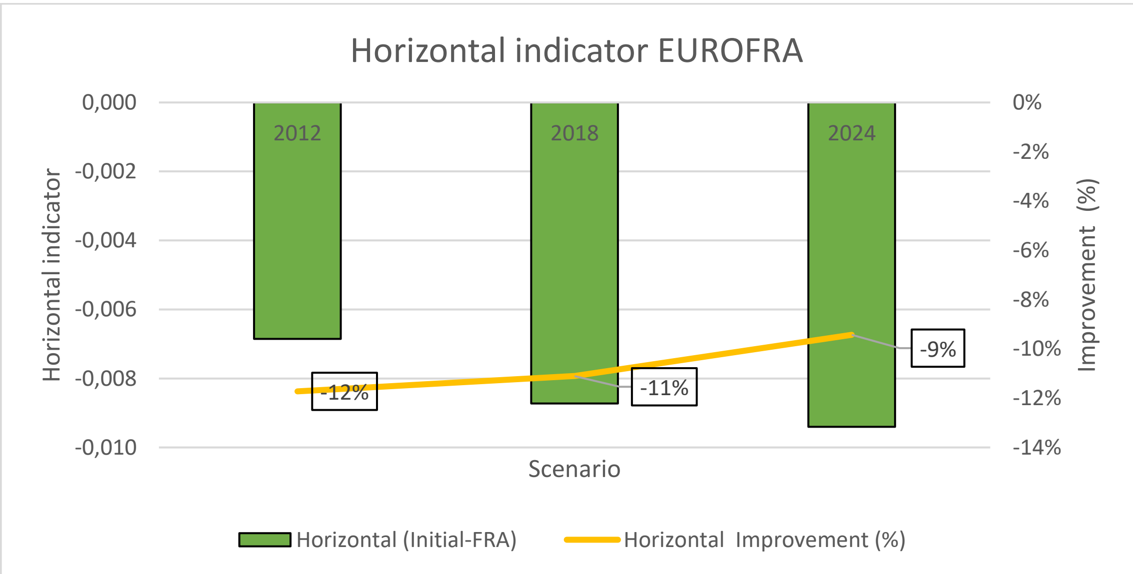

Figure 6.33 EUROFRA horizontal indicator

In Figure 6.34, for the speed interaction indicator, simulations with the EUROFRA scenario indicate improvements in the values. With less traffic in 2012, this represents an improvement of 21%, and with the highest number of flights in 2024, the speed interactions values are improved to 48%.

These improvements, imply reductions of traffic mix, providing a better separation between traffic velocities and reducing complexity and how it is managed.

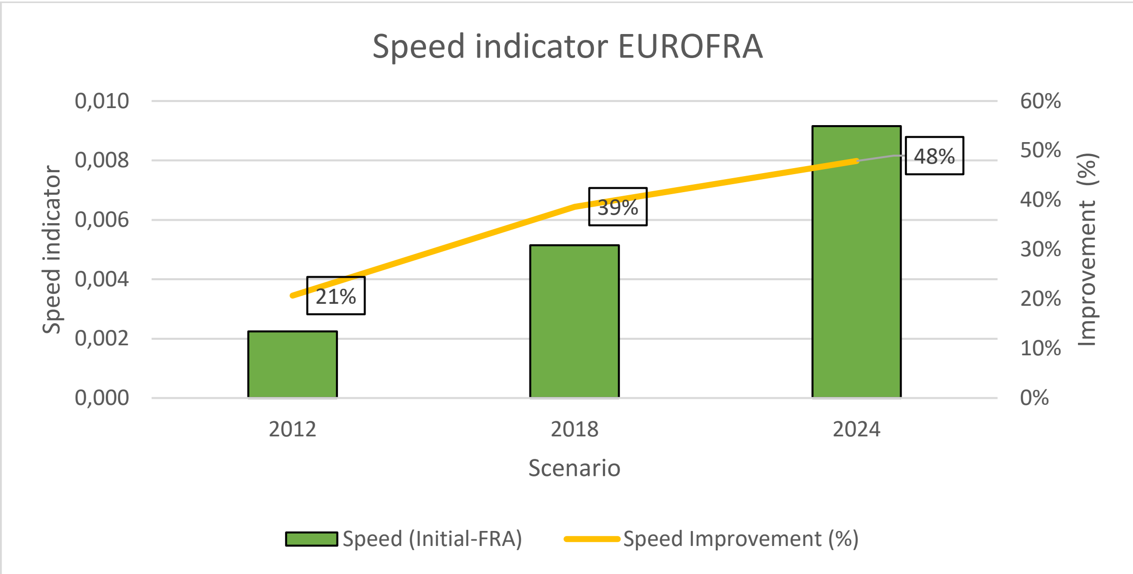

Figure 6.34 EUROFRA speed indicator

6.3.5.3. EUROFRA Structural Index and Complexity Score

The structural index results from EUROFRA are described in Figure 6.35, demonstrating that full free-route implementation in Europe will not increase the complexity values regarding interactions. This is based on the freedom for preferred route provided to airspace users, permitting traffic dispersion, and consequently, minor values of interactions between flight trajectories.

As presented in Figure 6.35, structural index values improve as the traffic increases. This is due to how controlled flight hours compensate for the values of increasing interactions, which do not grow at the same ratio as the number of flights.

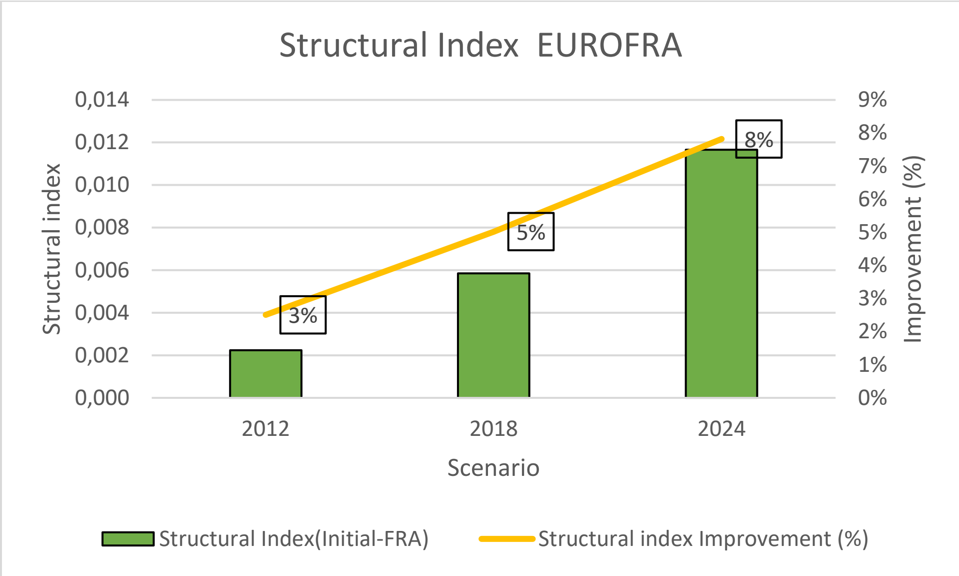

Figure 6.35 EUROFRA structural index

An interesting point of note from last figure is that even previous results demonstrate notable increases in the horizontal interactions. The general results for vertical and speed interaction benefits provide a better structural index result.

In addition, the results from the complexity score confirm the hypothesis that FRA does not make the airspace more complex. Rather, free route enables avoiding the bottlenecks and hot spot points that ATS fixed airway structures always face.

In this sense, the increases in horizontal crossings are compensated by the reduction of vertical interactions and traffic mix by speeds, resulting in a less complex airspace.

Figure 6.36 presents the complexity score values from simulations for the EUROFRA scenario:

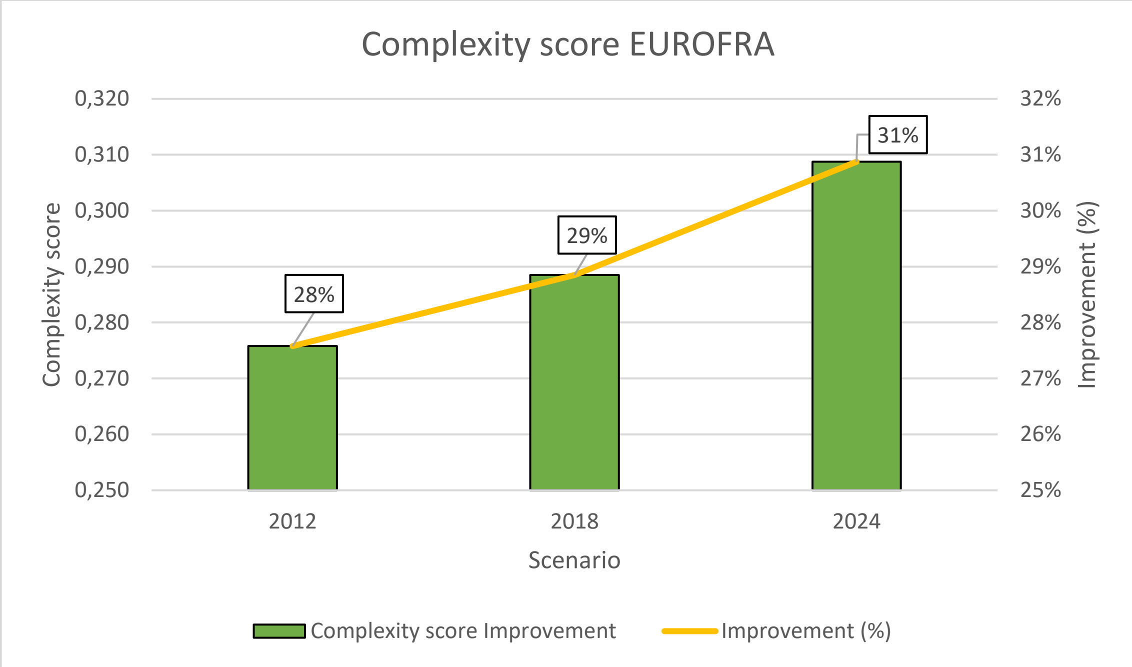

Figure 6.36 EUROFRA complexity score

From Figure 6.36, it can be stated that, with a full FRA block, complexity could be reduced by 30% regardless of increases in traffic.

The summarised results are presented in APPENDIX A – Detailed Results.

7. Conclusions

7.1. Main Results and Conclusions

The study of FRA using fast time simulations facilitates knowing and understanding the concept and the effects of its implementation on the ATM system. In this sense, flight distance and flight time savings were studied by comparing both scenarios (fixed airways network versus full free route). These results were translated into emissions savings, presented throughout this thesis.

From the ATC perspective, conflicts and complexity were evaluated in all scenarios, providing clear indicators of how complex or conflicting the airspace is made after free route is implemented.

A brief summary and conclusions of the achieved results, along with future work that could be undertaken based on the research accomplished in this thesis, are presented in this chapter.

7.1.1 Distance Saving

The results indicate that, with full free route implemented in NEFRA, airspace users can expect savings approximating 5100 NM with a traffic prognosis of 2024, presenting an improvement of 0,22% compared to the previous scenario. For SW FAB, simulations results indicate that distance saving range between 12.800 and 14.000 NM.

For the futuristic scenario named EUROFRA, distance savings results demonstrate decreases from 1,06 to 1,30% in flight distances compared to an airspace with partial free route and fixed airway networks.

These results clearly demonstrate benefits from the free-route perspective, as expected, but the approach benefit for a full European FRA has not been calculated prior to this work.

Results also demonstrate that, for a **EUROFRA scenario (full European free route), with a 2024 traffic prognosis of 32.000 flights per day, distance savings could reach approximately 547.000 NM per day.**

It is important to note that simulation results in this thesis were produced while only considering structural constraints as waypoint configurations and separations, without traffic flow and time restrictions, and with the hypothesis of a full free route without national borders operating. As such, this could differ from other estimations, such as presented by Bucuroiu (Bucuroiu, 2017) , who found that, by mid-2016, the daily European network savings potential would reach approximately 30000 NM, resulting in yearly savings of roughly 7.5 million NM considering partial and fixed ATS airways.

The potential benefits of free route presented in this thesis can also be supported by the operating side, as a previous academic and airline project (Mas-Mascolo & Riera, 2018) demonstrated that the economic savings linked to an airline—in this case, Vueling—even if FRA is not yet totally implemented, could reach an order of 400.000 € in savings per day. These savings come only from FRA utilisation of approximately 7% of the airline daily route distance.

7.1.2 Flight Time and Emission Saving

Regarding flight time and emission savings, the results indicate that, for flight time under the EUROFRA scenario, savings approach 20 to 40 flight hours per day depending on applied traffic load.

For specific environments, the NEFRA simulation demonstrates that flight time savings could range from 1,6 to 0,91% in total flight time compared to the previous scenario without free route.

For SW FAB, results demonstrate improvements between 3,22 and 3,92% compared to initial traffic samples, translating to 85–179h flight hours in savings.

The importance of calculating the flight time rests on the ability to translate this into to fuel consumption and emission estimations, providing an overview of much could be saved by applying the free-route concept.

Thesis calculations indicate that, with **full European FRA,** it is possible to saves **85 tons of fuel per day, further resulting in savings of 266 tons of C02 and 67 tons in NOx emissions.** It should further be noted that the results indicate a macroscopic implementation.

These results contrasted with other research, such as conducted by Aneeka and Zhong (Aneeka & Zhong, 2016), who found different ratios of emission savings with free-route implementation. These differences could be explained by previous studies applying the free-route characteristic in a less optimised scenario—namely, the ASEAN—as well as by the use of only 57% of free-route trajectories compared to the nearly 100% generated by this thesis.

With all this, this thesis confirms the free route's benefits in flight time savings for airlines and airspace users, as well as the significant reductions in greenhouse gasses resulting from aircraft emissions.

7.1.3 Conflicts

Regarding conflict estimation, this thesis demonstrates three main results:

- **Free route does not increase the total number of conflicts** compared to previous scenarios where partial FRA or fixed airway networks continue to operate.

The results indicate that, for NEFRA, SW FAB and EUROFRA, potential conflicts are reduced in number through the implementation of free route.

Particularising for the EUROFRA scenario, these reductions ranged from 11 to 17%, with similar ratios registered for NEFRA and SW FAB.

For the network manager (Eurocontrol), expectations in conflict and ATC workload remain quite similar to the thesis results. Bucuroiu (Bucuroiu, 2017) also mentioned that free-route implementation produces some benefits for ANSP, all concerning ATC workload, with no expected impact on ATC workload, and in some instance, there was an expected reduction in this issue.

- **Free route increases the number of conflicts related to horizontal crossing** and, consequently, all conflicts in the horizontal dimension.

Simulation results indicate that the horizontal conflicts were increased with the application of free route to all scenarios. Specifically, the potential conflicts concerning cruise and crossing conflicts were increased from approximately 40 to 50%. Consequently, a decrease of the same ratio was registered in the parallel conflicts.

- **Free route resulted in marginal reductions in the number of vertical conflicts**, particularly evolving cruise conflicts.

The thesis results indicate that, after free-route implementation, the vertical conflicts related to climbing/cruise status aircrafts are reduced by 20% in the best scenario (EUROFRA, 2024), but in general, reduction is around 10–15% in NEFRA and SW FAB calculations.

In general, conflict results were contrasted with other similar studies (Ruiz, Lopez-Leones, & Ranieri, 2018), (Netjasov, Crnogorac, & Pavlović, 2019) regarding free route and conflicts and ECAC scenarios, finding similar rations of conflicts and traffic in their calculations.

7.1.4 Complexity

The complexity results from this thesis demonstrate important issues for consideration in free-route implementation areas.

As described in previous theories (Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis, 2006), the two main metrics defining the complexity score (global complexity) consist of adjusted density and structural index.

The adjusted density evaluates the potential interactions resulting from density, including uncertainty in the trajectories and time, while the structural index balances the density metrics according to the interaction geometry and aircraft performance differences.

The employed metrics reflect the difficulty of simultaneously managing the presence of several aircraft in the same area, particularly if those aircraft are in different flight phases, feature different performances, and/or possess different headings.

As summarised, the following represent the most important results regarding complexity:

- In general, **adjusted density tends to decrease with FRA**, even with highest traffic loads, as simulated in 2024 in EUROFRA, or in more dense zones such as NEFRA, where adjusted density is reduced with free route.

Adjusted density relates to the potential number of interactions per volume of airspace in the case of scenarios simulated. The constant increase in controlled flight hours related to the increase in flight number does not increase at the same ratio as interactions, resulting in a reduction of traffic density. The main explanation for this result concerns the dispersion phenomena that free-route trajectories follow. By nature, the preferred trajectories used in simulations are based on reducing distance or flight, with more DCT (Direct Course to Route) avoiding all the problems presented in airway networks, such hot spots, resulting in fewer interactions in the en-route cells evaluated.

Results indicate that, in the EUROFRA scenario, adjusted density is reduced by approximately 25%. For NEFRA, results are less favourable, with reductions ranging from 4% to nearly zero values. In addition, for the SW FAB, adjusted density results indicate that free route could notably increase those values. Results from adjusted density in SW FAB demonstrate negative differences between 5 and 6%.

A similar approach to this thesis (Rezo & Steiner, 2019) maintained that the pattern of spatial distribution in free route is random and that clusters do not exist.

- The **vertical interactions** indicator, that is related with the potential interactions between climbing, cruising and descending aircraft (< 500 ft), it is **reduced with free route implementation.**

Simulations indicate that, with EUROFRA, reduction in vertical complexity approaches 30–35%, and 20-24% for NEFRA. For the SW FAB, results demonstrate that the vertical interactions were reduced between 37 and 62%. If these vertical complex results are linked to those presented for conflicts in the vertical dimension, it is confirmed that the vertical crossing between evolving trajectories with cruise or another evolving traffic is reduced in free route, indicating a traffic stratified by FL and with low interactions and changes.

The relevant reduction in vertical interactions is not all valid for 2024 traffic sample results because, as explained in chapter three (FIPS algorithm), it derives from a traffic prognosis that clones the flight levels in an original base trajectory.

- In the case of the **horizontal interactions**, **free route simulations demonstrated that are increased** in all scenarios and traffic samples, evidencing the point discussed before with conflicts in horizontal dimensions, with free route, trajectory crossings are increased and resulting in horizontal complexity increments.

Thesis results indicate that, in EUROFRA, horizontal interactions are increased between 9 and 12%. For NEFRA, increases range between 6 and 9%. Finally, for the SW FAB, the increase in complexity interactions approach 16–20%.

These results are supported by other qualitative studies (Antulov-Fantolin, Rogosic, Juricic, Billiana, & Andrasi, 2018) (Nava-Gaxiola, C.; Barrado, C., 2016), which concluded that, with FRA implementation, traffic complexity is increased (from the horizontal dimension), and that controllers face difficulty in detecting conflicts in advance, since there are no more old 'hotspots' to concentrate on. Hence, the entire airspace is considered a hotspot.

- Speed interaction results relate to potential interactions based on the aircraft (> 30 kt) difference. In this sense, **simulations indicate that, with the free-route scenario, speed interactions tend to reduce** by 21 to 48% in EUROFRA and by 54% in NEFRA airspace with 2024 traffic samples. In the case of SW FAB, results demonstrate that FRA reduces between 24 and 79%.

The speed interactions, as horizontal and vertical, possess the same weight in structural and complex calculations, as the indicators result from adjusted density values.

- Regarding structural index, in general, **calculations indicate that the structural index is lower with free-route scenarios**, implying that the resulting complexity from vertical, horizontal and speed interactions does not increase as much commented in the qualitative studies mentioned before. This confirms that the interaction geometry and aircraft performance differences in FRA are lower with the comparative scenarios (airway fixed network or partial FRA).

The overall thesis results demonstrate that the structural index in NEFRA passed from negative values (increased) to approximately 10% reductions with the highest traffic in 2024. For the EUROFRA simulations, those values continually demonstrated reductions from 3 to 8%. Concerning SW FAB, the structural index approached positives values between 2,78 and 13%.

The SW FAB analysis indicates that the structural airspace limits the complexity interactions. Thus, the SW FAB scenario presented steady behaviour in the structural index, as also reflected in the complexity score value.

- The final values of this thesis relate to the complexity score, which offers an expression of the structural index, but independent of the FT (controlled flight hours). This means that it reflects the complexity regardless of the traffic volume.

After structural index calculations, the global complexity scores remained quite similar. For each scenario, **complexity score tended to reduce with FRA.**

In the EUROFRA scenario (full European FRA), the complexity score was reduced by 30% in all traffic samples, affirming that free route does not increase the global complexity of the airspace.

The results for NEFRA exhibited reductions until 10% with the maximum traffic load, and for the SW FAB, results demonstrated favourable results around five to six with the two highest traffic sample scenarios.

7.2. Thesis Contributions

The main contribution of this thesis concerns its **novel approach and evaluation of a full FRA scenario** in the **European airspace.** This study not only evaluates benefits already known for airspace users, but it deepens the conflict and complexity analysis in order to develop an overview of the main characteristics that a full free-route scenario operating in Europe could possess.

Deriving from this study's results, it could be concluded that **airspace users experience great benefits from free-route implementation**, including important distance savings that can reach 1,30% of the nominal route in a full European free route.

Regarding complexity, this thesis provides important results for free-route implementation, stating that **horizontal complexity and conflicts will be increased** by FRA, as the **airspace trajectories and flows become more random, increasing the crossing interactions.** On the other hand, however, **the vertical and speed interactions notably decrease, producing a global reduction in complexity.**

Another important contribution of this thesis concerns the **evidence** it obtains from different scenarios (NEFRA, SW FAB and ECAC area), finding that **airspace fragmentation penalised airspace users and ANSPs, reducing benefits and augmenting complexity.** This thesis further concludes that state boundaries represent a limitation for the operational improvements proposed in the SESAR programme concerning SES modernisation. In this way, the FAB represents the SESAR organisational concept that aims at eliminating this drawback.

Added to this PhD thesis, a previous qualitative study (Nava-Gaxiola, C.; Barrado, C., 2016) provided **qualitative comments from ATC interviews** stating that **FRA increases complexity.** However, this has been **rebutted by this thesis**, which **demonstrated that complexity increases only in the horizontal dimension**, while general complexity is reduced.

An additional contribution of this dissertation derives from its **application** of the **PRU complexity concepts** from Eurocontrol, determining all the complex parameters from current and new designed airspaces.

7.3. Guidelines for Future Works

During this PhD thesis, new questions and research lines arose. As such, the following points elaborate on guidelines proposed for future works:

- Deriving from this thesis, a deeper exploration of free-route application in the lowest FL—under FL 200—will provide better performance and freedom to airspace users. However, the effects of applying free route at a lower level remain unknown. More complexity is expected, particularly in the vertical dimension, increasing traffic mixing, but this raises the question of what the lowest limit is in which free route can be applied. Furthermore, it needs to be determined what complexity limits can be afforded by the ATM system.
- Another point for future works involves calculating the optimal FRA block size in order to explore the best operational airspace block size in free route to provide gains to users and ANSPs.
- Applying the free-route concept to new environments, such as UTM (Unmanned Traffic Management) requires performing fast time simulations based on the free-route principle, including user-preferred trajectories based on 'entry/exit points', supported by 'intermediate' waypoints under a deconflicting system.
  Extrapolating the free-route concept to UTM systems could be analysed by studying different aspects, such as benefits and conflicts/complexity issues.

8 Summary of Publications

Journal Papers

- Nava-Gaxiola C.A., Barrado C., Royo P. and Pastor E. (2018, August 20). Assessment of the North European free route airspace deployment. *Journal of Air Transport Management, 73*, 113-119.

- Nava-Gaxiola César: Barrado, C. (2016). Performance measures of the SESAR Southwest functional airspace. *Journal or Air Transport Management Elsevier, 50*, (50) 21-29.

Conference Proceedings

- Nava-Gaxiola, C., Barrado, C., & Royo, P. (2018). Study of a Full Implementation of Free Route. *2018 IEEE AIAA Digital Avionic Systems Conference (DASC).* London, UK.

- Nava-Gaxiola, C., & Barrado, C. (2016). Free Route Airspace and the need of new Air Traffic Control Tools. *DASC.* Sacramento, CA.

9 References

Alam, S., Lokan, C., H, A., Ellejmi, M., & Kirby, S. (2010). An evolutionary computational analysis of tactical controller tool. *Eurocontrol and University of New South Wales*.

Aneeka, S., & Zhong, Z. W. (2016). NOX and CO2 emissions from current air traffic in ASEAN region and benefits of free route airspace implementation. *Journal of Applied and Physical Sciences*, 2016, 2(2):32-36.

Antulov-Fantolin, B., Rogosic, T., Juricic, Billiana, & Andrasi, P. (2018). Air Traffic Controller Assessment of Free Route Airspace Implementation within Zagreb Area Control Centre.

Bucuroiu, R. (2017). A Free Route Airspace for Europe. *WAC 2017 (EUROCONTROL).* EUROCONTROL.

Button, K., & Neiva, R. (2013, Octuber). Single European Sky and the functional airspace blocks: Will they improve economic efficiency? *Journal of Air Transport Management, 33*, 73-80.

Chatterji, G. S. (2001). Measures for air traffic controller workload prediction. *In: 1st AIAA, Aircraft, Technology Integration, and Operations Forum, Aviation Technology, Integration, and Operations (ATIO) Conferences, vol. 2001.*

De Herdt, D. E. (2018, May). *Free Route Airspace Maastricht (FRAM).*

De Prins,J. and Gómez Ledesma, R. (2008). Literature review of air traffic controller modeling for traffic simulations. *DASC*.

Denmark ANSP. (2019). Retrieved from http://www.naviair.dk/

Dowek.G, L.C, C., & Geser.A, M. a. (2001). Tactical conflict detection and resolution in a 3-D. *NASA*.

Drupka, G., Majka, A., Rogalski, M., & Trela, L. (2018). AN AIRSPACE MODEL APLICABLE FOR AUTOMATIC FLIGHT ROUTE PLANNING INSIDE FREE ROUTE AIRSPACE. *ESZYTY NAUKOWE POLITECHNIKI RZESZOWSKIEJ 298*, 5-18.

Estonia ANSP. (2019). Retrieved from http://eaip.eans.ee/2019-09-12/html/index-en-GB.html

Eurocontrol . (2018 a). FIR/UIR in the Upper Airspace (EUROCONTROL Member States).

Eurocontrol. (2005). *To Support the Establishment of Functional Airspace Blocks FABs.*

Eurocontrol. (2011, Summer-Autumn). Designing and managing airspace routes. *Eurcontrol:Skyway Magazine*(55), 7-8.

Eurocontrol. (2011, February). The Single European Sky.

Eurocontrol. (2012). *Single European Sky – Frequently Asked Questions.* Brussels, 11 October 2012.

Eurocontrol. (2016, April). *Maastricht Upper Area Control Centre*. Retrieved from https://eurocontrol.int/sites/default/files/publication/files/muac-factsheet-2016.pdf

Eurocontrol. (2018 b). *Free route airspace (FRA)*. Retrieved from https://www.eurocontrol.int/articles/free-route-airspace

Eurocontrol. (2018 c, October). *Free Route Airspace (FRA) Implementation projections*. Retrieved from https://www.eurocontrol.int/publications/free-route-airspace-fra-implementation-projections

Eurocontrol. (2018 d). *Free Route Airspace at Maastricht UAC*. Retrieved from https://www.eurocontrol.int/free-route-airspace-maastricht-uac

Eurocontrol. (2018 e). Retrieved November 5, 2018, from Functional Aispace Block (FAB): https://www.eurocontrol.int/articles/functional-airspace-block-fab

Eurocontrol. (2018). *NEST User Manual, Version 1.6.*

Eurocontrol. (2018). *Seven-Year Forecast 2018.*

Eurocontrol. (2019). *Demand Data Repository*. Retrieved from https://www.eurocontrol.int/ddr

Eurocontrol, Complexity Metrics for ANSP Benchmarking Analysis. (2006). *Complexity Metrics for ANSP Benchmarking Analysis.* Performance Review Commission (PRC). Retrieved from https://www.eurocontrol.int/publications/report-complexity-metrics-ansp-benchmarking-analysis

European Civil Aviation Conference. (2014). Retrieved from https://www.ecac-ceac.org/member-states

European Civil Aviation Conference. (2019). *ECAC*. Retrieved from https://www.ecac-ceac.org/member-states

European Comission. (2018 d, November). *Mobility and Transport*. Retrieved from Single European Sky II: https://ec.europa.eu/transport/modes/air/single_european_sky/ses_2_en

European Comission. (2018 e). *The BOREALIS alliance: Delivering FRA across Northern Europe by 2021*. Retrieved from https://ec.europa.eu/transport/modes/air/ses/ses-award-2016/projects/fra_en

European Commission. (2000). *Report of high-level group.* Directorate General for Energy and Transport, Single European Sky.

European Commission. (2018 a, December 5). Retrieved from https://ec.europa.eu/transport/modes/air/single-european-sky/functional-airspace-blocks-fabs_en

European Commission. (2018 b, November 4). *European Commission > Transport > Transport modes > Air > Single European Sky*. Retrieved November 5, 2018, from European Commission: https://ec.europa.eu/transport/modes/air/single_european_sky_en

European Commission. (2018 c). *Functional airspace blocks (FABs)*. Retrieved from https://ec.europa.eu/transport/modes/air/single-european-sky/functional-airspace-blocks-fabs_en

European Commission. (2018 e, November 29). *SESAR Deployment Phase launched*. Retrieved from https://ec.europa.eu/transport/modes/air/sesar_en

European Commission and Eurocontrol. (2015). *2015-European ATM Master Plan.*

European Commission. (Regulation (EC) No 409/2013).

European Commission. (Regulation (EC) No 549/2004).

European Commission. (Regulation (EC) No 550/2004).

European Commission. (Regulation (EC) No 551/2004).

European Commission. (Regulation (EC) No 552/2004).

European Commission. (Regulation (EC) No 716/2014).

European Commission. (Regulation (EU) No 1070/2009).

European Commission. (Regulations (EU) No 219/2007).

FAA and Eurocontrol. (2019). *2017-Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe.*

Finland ANSP. (2019). Retrieved from https://www.ais.fi/fi

Flenera, P. P.-A. (2007). Air traffic complexity resolution in multi-sector planning. *J. Air Transport. Management*, 13 (6),323–328 November 2007.

Gaydos, T. L. (2013). Analysis of conflict detection performance for trajectory-based descent operations. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Geser,A.; C. Muñoz. (2002). A geometric approach to strategy conflict detection and resolution. *ICASE - NASA Langley Research Center*.

Gurtner, G. B. (2017). An empirically grounded agent based simulator for the air traffic management in the SESAR scenario. *Journal of Air Transport Management*, Volume 59, March 2017, Pages 26-43.

Henn, A. (2015). Experience and Recommendations from a CFSP.

Holstila, J., & Andersson, A. (n.d.). *NEFRA Expert and Implementation Gruop*. Retrieved from https://www.nefab.eu/uploads/content/files/559b860a5cd32.pdf

IATA, A. E. (2011). *A Blueprint for the Single European Sky.*

ICAO. (2008). *Manual on Global Performance of the Air Navigation System.*

ICAO. (2017). *Task Force (AIRARDTF/02)*. Retrieved from Second Meeting of the Advanced Inter-Regional ATS Route Development.

ICAO, Annex 11 Air Traffic Services. (2001). Chapter 2, Section 2.6.

ICAO, Doc. 4444 AIr Traffic Management. (2016). *Doc 4444 AIr Traffic Management.*

Idris, H. S. (2013). Estimating airspace capacity based on risk mitigation metrics. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

IVAO. (n.d.). *Airspace Structure*. Retrieved from https://www.ivao.aero/training/documentation/books/Student_Airspace_structure.pdf

Kelly III, W.E.;Collins R. (1999). Conflict detection and alerting for separation assurance systems. *DASC*.

Knorr, D. C. (2011). Estimating ATM efficiency pools in the descent phase of flight. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Kopardekar, P. S. (2009). Airspace complexity measurement: an air traffic control simulation analysis. *International Journal of Industrial Engineering*, 16 (1), 61–70.

Krug, J. (n.d.). *Clearance Through Class B, C, D Airspace*. Retrieved from https://pilotworkshop.com/tips/atc_airspace_entry/

Kuchar, J., & Yang, C. a. (2000). A Review of Conflict Detection and Resolution Modeling Methods. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 1, No. 4, pp. 179-189.

Kwangyul, B., & Hyochoong, B. (2012). ADS-B based Trajectory Prediction and Conflict Detection for Air Traffic. *International Journal of Aeronautical & Space Science*, Vol 3(3), 377–385.

Latvia ANSP. (2019). Retrieved from https://ais.lgs.lv/

Lee, P. B. (2011). Benefits and feasibility of the flexible airspace management concept: a human-in-theloop evaluation of roles, procedures, and tools. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Majumdar, A. O. (2005, November). En-route sector capacity estimation methodologies: an international survey. *J. Air Transport. Management*, 11 (6), 375–387.

Marco, R., Sánchez, P., & Prats, X. (2017). New approaches to ATM performance analysis: overview of the APACHE, AURORA and INTUIT projects. *Poster in the 7th SESAR Innovation Days*.

Mas-Mascolo, A., & Riera, A. (2018). *Estudi teòric i econòmic del Free Route Airspace.* Universitat Politecnica de Catalaunya and Vueling Airlines.

McNally, D. e. (2013). Operational evaluation of dynamic weather routes at american airlines. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Mihetec, T., et al. (2012). Analysis of Expected ATM Processes Changes in Central Europe. 4-12.

Mirkovic, B., Pavlovic, G., Netjasov, F., Babic, O., Barrado, C., Prats, X., . . . Vidosavljevic, A. (2017, November). Measuring Performance of the European Air Traffic Management System Review of current performance indicators and proposal for new ones. *Poster in the 7th SESAR Innovation Days*.

Nava-Gaxiola, C., & Barrado, C. (2016). Performance measures of the SESAR Southwest functional airspace. *Journal or Air Transport Management Elseveir, 50*, (50) 21-29.

Nava-Gaxiola, C.; Barrado, C. (2016). Free Route Airspace and the need of new Air Traffic Control Tools. *DASC.* Sacramento, CA.

Nava-Gaxiola, C.; Barrado, C.; Royo, P. (2018). Study of a Full Implementation of Free Route. *2018 IEEE AIAA Digital Avionic Systems Conference (DASC).* London, UK.

Nava-Gaxiola, C.;Barrado, C.; Royo, P. and Pastor, E. (2018, August 20). Assessment of the North European free route airspace deployment. *Journal of Air Transport Management, 73*, 113-119.

Netjasov, F., Crnogorac, D., & Pavlović, G. (2019). Potential safety occurrences as indicators of air traffic management safety performance: A network based simulation model. *Transportation Research Part C*, Vol 102 (2019), pages 490–508.

Netjasov, F.; Crnogorac, D. (2017, September). Assessment of safety performance indicators of future air traffic management system. *Proceedings of the XLIV Symposium on operational research (SYM-OP-IS).*

Norway ANSP. (2019). Retrieved from https://avinor.no/en/

ONATAP . (2011). *AIRE Performance of flight trials and demostrations validing solutions for the reduction of CO2 emission.*

Pan, R., & Lishuai, L. (2018). Characterizing air traffic networks via large-scale aircraft tracking data: A comparison between China and the US networks. *JATM*, Vol 69, Pages 181-196.

Pappie, G. (2018). *Benefits of Direct routes above Europe.* TU Delt University.

Pavlova, S., & Zadorozhnia, A. (2014). *ANALYSIS OF FREE ROUTE AIRSPACE AND PERFORMANCE BASED NAVIGATION IMPLEMENTATION IN THE EUROPEAN AIR NAVIGATION SYSTEM* (Vols. 2014. N 4(61): 28–35). Proceedings of the National Aviation University (Ukraine).

Pechenik, Y. (. (2019). UNLOCKING NEW LEVELS OF CAPACITY BY DYNAMIC AIRSPACE DESIGN. *Skyway*, Vol 70, pag 29.

Pozzi, S. V. (2011). Safety monitoring in the age of big data. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Prats, X., Barrado, C., Vidosavljevic, A., Delahaye, D., Netjasov, F., & and Crnogorac, D. (2017, November). Assessing ATM Performance with Simulation and Optimisation Tools: The APACHE Project. *proceedings of the 7th SESAR Innovation Days*.

Ramazan Kursat, C., & Cetek, C. (2019). A Two-Step Approach for Airborne Delay Minimization Using Pretactical Conflict Resolution in Free-Route Airspace. *Journal of Advanced Transportation*, Volume 2019, Article ID 4805613, 17 pages.

Reynolds, T. G. (2009). Development of flight inefficiency metrics for environmental performance assessment of ATM. *8th USA/Europe Seminar on Air Traffic Management Research and Development*.

Rezo, Z., & Steiner, S. (2019). European airspace complexity and fragmentation correlation research. *Conference venue: Hungarian Academy of Sciences, Budapest.* Budapest, Hungary.

Ruiz, S., Lopez-Leones, J., & Ranieri, A. (2018). A Novel Performance Framework and Methodology to Analyze the Impact of 4D Trajectory Based Operations in the Future Air Traffic Management System. *Journal of Advanced Transportation*, Volume 2018, Article ID 1601295, 17 pages.

Ryerson, M. H. (2011). Fuel consumption and operational performance. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Schäfer, D. M. (2003). A Human Factors Perspective on Free Routing and Airborne Separation Assurance in the Mediterranean Airspace. *ATM Seminar* .

Schäfer, D., Modin, E., & Scrivani, W. e. (2003). A human factor perspective of free routing and airborne separation assurance in the mediterranean airspace.

Skybrary. (2017, July). *Free Route Airspace (FRA)*. Retrieved from https://www.skybrary.aero/index.php/Free_Route_Airspace_(FRA)

Skybrary. (2017, August 2). *Sectorisation*. Retrieved from https://www.skybrary.aero/index.php/Sectorisation

Skybrary. (2017, July 31). *SESAR_Joint_Undertaking*. Retrieved from https://www.skybrary.aero/index.php/SESAR_Joint_Undertaking

Steiner, S., Mihetec, T., & Rezo, Z. (2019). Resolution of Operational Constraints Imposed by Fragmentation of European Airspace. *International Scientific Conference Science and Traffic Development (ZIRP 2019).* Opatija, Croatia.

SW FAB . (2019). *SW FAB*. Retrieved from Operations: http://www.swfab.eu/operations-20141122230918

SW FAB Operational Board. (2015). *Operational Board Common Plan 2015_2019.*

Sweden ANSP. (2019). Retrieved from https://aro.lfv.se/

Timar, S. H. (2013). Assessing the benefits of NextGen performance based navigation (PBN). *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Toy, J. (2015). Complexity Metric Comparison Study for Controller Workload Prediction in 4D Trajectory Management Environments. *MSc Thesis at Delf University of Technology*.

Vaze, V. B. (2011). A multi-stakeholder evaluation of strategic slot allocation schemes under airline frequency competition. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Vogel, M. S. (2013). Analysis of airspace complexity factors,capability to predict workload and safety levels in the TMA. *In: Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Welch, J. C. (2013). Sector workload model for benefits analysis and convective weather capacity prediction. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Wilmer, C. P. (2001, May). *Study of the European Commission on the regulation and airspace design.*

Wojcik, L. M. (2013). Flexibility metrics and their application to departure queue management. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Xie, Z., Aneeka, S., Lee, Y. X., & Zhong, Z. W. (2017). International Journal of Advanced and Applied Sciences. Vol 4(12) 2017, Pages: 10-15.

Yifei, Z. D. (2011). Method to analyse air traffic situation based on air traffic complexity map. *9th USA/Europe Air Traffic Management Research and Development Seminar*.

Yi-Jen, C., Klosowski, J., Lee, C., & Mitchell, J. (1997). Geometric algorithms for conflict detection/resolution in air traffic management. *University of NY*.

Zanin, M. (2013). Synchronization likelihood in aircraft trajectories. *Tenth USA/Europe Air Traffic Management Research and Development Seminar*.

Zou, B. E. (2013). Evaluating air carrier fuel efficiency in the U.S. Airline Industry. *Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)*.

10 APPENDIX A – Detailed Results

CONFLICT RESULTS

- NEFRA

	Sample	Initial conflicts	Free route conflicts	Free route conflict Improvement	Free route conflict Improvement (%)
2012	Day 1	233	221	12	5%
	Day 2	205	196	8	4%
	Day 3	259	223	36	14%
	Day 4	224	209	15	7%
	Day 5	243	237	5	2%
	Day 6	171	178	-7	-4%
	Day 7	209	196	13	6%

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2018	Day 1	287	277	10	4%
	Day 2	285	274	11	4%
	Day 3	278	250	28	10%
	Day 4	274	259	15	5%
	Day 5	299	276	23	8%
	Day 6	236	215	21	9%
	Day 7	277	247	30	11%

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2024	Day 1	501	389	112	22%
	Day 2	464	377	87	19%
	Day 3	447	364	83	18%
	Day 4	430	350	80	19%
	Day 5	444	383	62	14%
	Day 6	460	377	83	18%
	Day 7	397	335	62	16%

NEFRA 2012

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	11	10	2%
Evolving / Evolving Opposite	0	0	-10%
Evolving / Evolving Crossing	2	3	-16%

Evolving / Cruise Parallel	18	13	25%
Evolving / Cruise Opposite	8	7	11%
Evolving / Cruise Crossing	14	13	3%
Cruise / Cruise Parallel	15	13	13%
Cruise / Cruise Opposite	3	4	-39%
Cruise / Cruise Crossing	30	36	-22%

NEFRA 2018

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	11	10	14%
Evolving / Evolving Opposite	1	1	-63%
Evolving / Evolving Crossing	2	3	-26%
Evolving / Cruise Parallel	14	11	20%
Evolving / Cruise Opposite	7	6	18%
Evolving / Cruise Crossing	18	16	9%
Cruise / Cruise Parallel	14	13	7%
Cruise / Cruise Opposite	2	3	-20%
Cruise / Cruise Crossing	31	38	-22%

NEFRA 2024

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	13	11	16%
Evolving / Evolving Opposite	0,5	0,8	-80%
Evolving / Evolving Crossing	3	3	-16%
Evolving / Cruise Parallel	12	10	19%
Evolving / Cruise Opposite	7	5	35%
Evolving / Cruise Crossing	17	17	1%
Cruise / Cruise Parallel	15	15	3%
Cruise / Cruise Opposite	2	2	-3%
Cruise / Cruise Crossing	31	38	-22%

2012			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	13	13	1%
Evolving / Cruise	39	34	-17%
Cruise/ Cruise	47	53	11%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	43	37	-18%
Opposite	11	11	1%
Crossing	46	52	12%

2018			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	14	14	4%
Evolving / Cruise	39	33	14%
Cruise/ Cruise	47	53	-13%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	39	33	14%
Opposite	10	10	4%
Crossing	51	57	-11%

2024			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	-13%	-13%	-13%
Evolving / Cruise	-13%	-13%	-13%
Cruise/ Cruise	-13%	-13%	-13%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	40	35	12%
Opposite	9	7	23%
Crossing	51	58	-14%

- SW FAB

	Sample	**Initial conflicts**	**Free route conflitcs**	**Free route conflict (Improvement)**	**Free route conflict Improvement (%)**
2012	**Day 1**	364	292	72	19,8%
	Day 2	383	268	115	30,0%
	Day 3	378	293	85	22,5%
	Day 4	407	358	49	12,0%
	Day 5	436	342	94	21,6%
	Day 6	494	349	145	29,4%
	Day 7	472	390	82	17,4%

	Sample	**Initial conflicts**	**Free route conflitcs**	**Free route conflict (Improvement)**	**Free route conflict Improvement (%)**
2018	**Day 1**	863	653	210	24,3%
	Day 2	751	541	210	28,0%
	Day 3	747	517	230	30,8%
	Day 4	891	616	275	30,9%
	Day 5	782	565	217	27,7%
	Day 6	863	631	232	26,9%
	Day 7	884	663	221	25,0%

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2024	**Day 1**	1427	1155	272	19,1%
	Day 2	1277	959	318	24,9%
	Day 3	1127	830	297	26,4%
	Day 4	1149	850	299	26,0%
	Day 5	1366	948	418	30,6%
	Day 6	1183	894	289	24,4%
	Day 7	1386	991	395	28,5%

SW FAB 2012

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	26	30	-15%
Evolving / Evolving Opposite	2	4	-70%
Evolving / Evolving Crossing	7	11	-64%
Evolving / Cruise Parallel	18	9	50%
Evolving / Cruise Opposite	6	5	24%
Evolving / Cruise Crossing	8	5	36%
Cruise / Cruise Parallel	19	17	11%
Cruise / Cruise Opposite	6	4	28%
Cruise / Cruise Crossing	9	16	-88%

SW FAB 2018

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	22	25	-15%
Evolving / Evolving Opposite	3	2	33%
Evolving / Evolving Crossing	7	8	-19%
Evolving / Cruise Parallel	17	9	50%
Evolving / Cruise Opposite	9	4	52%
Evolving / Cruise Crossing	10	6	40%
Cruise / Cruise Parallel	18	17	4%
Cruise / Cruise Opposite	5	8	-60%
Cruise / Cruise Crossing	10	21	-118%

SW FAB 2024

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	20	22	-11%
Evolving / Evolving Opposite	3	2	24%

Evolving / Evolving Crossing	7	8	-17%
Evolving / Cruise Parallel	16	9	47%
Evolving / Cruise Opposite	9	5	46%
Evolving / Cruise Crossing	10	7	31%
Cruise / Cruise Parallel	20	17	12%
Cruise / Cruise Opposite	6	9	-53%
Cruise / Cruise Crossing	10	22	-113%

2012			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	34	44	-28%
Evolving / Cruise	33	19	41,46%
Cruise/ Cruise	33	37	-12,33%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	62	55	12%
Opposite	14	12	12%
Crossing	24	33	-37%

2018			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	31	35	-12%
Evolving / Cruise	36	19	48%
Cruise/ Cruise	32	46	-43%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	62	55	12%
Opposite	14	12	12%
Crossing	24	33	-37%

2024			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	32	-9%	32
Evolving / Cruise	20	43%	20
Cruise/ Cruise	48	-34%	48
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	48	14%	48
Opposite	16	11%	16
Crossing	36	-36%	36

- EUROFRA

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2012	Day 1	7040	5992	1048	15%
	Day 2	6372	5638	734	12%
	Day 3	6791	5976	815	12%
	Day 4	6746	6034	712	11%
	Day 5	7244	6538	706	10%
	Day 6	7415	6824	591	8%
	Day 7	7306	6548	758	10%

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2018	Day 1	11201	9730	1471	13%
	Day 2	10458	9082	1376	13%
	Day 3	10564	8960	1604	15%
	Day 4	11189	9654	1535	14%
	Day 5	11635	9998	1637	14%
	Day 6	11720	10522	1199	10%
	Day 7	11731	10399	1332	11%

	Sample	Initial conflicts	Free route conflitcs	Free route conflict (Improvement)	Free route conflict Improvement (%)
2024	Day 1	20259	17129	3130	15%
	Day 2	18470	15393	3076	17%
	Day 3	17239	14282	2957	17%
	Day 4	17410	14128	3282	19%
	Day 5	18686	15180	3507	19%
	Day 6	19332	15851	3481	18%
	Day 7	19764	16850	2914	15%

EUROFRA 2012

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	7	6	12%
Evolving / Evolving Opposite	1	1	-23%
Evolving / Evolving Crossing	2	3	-42%
Evolving / Cruise Parallel	19	10	46%
Evolving / Cruise Opposite	7	6	17%
Evolving / Cruise Crossing	17	19	-12%
Cruise / Cruise Parallel	17	8	51%

Cruise / Cruise Opposite	3	4	-51%
Cruise / Cruise Crossing	28	43	-54%

EUROFRA 2018

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	6	5	20%
Evolving / Evolving Opposite	1	1	4%
Evolving / Evolving Crossing	2	3	-48%
Evolving / Cruise Parallel	17	7	56%
Evolving / Cruise Opposite	8	6	27%
Evolving / Cruise Crossing	18	19	-9%
Cruise / Cruise Parallel	17	8	54%
Cruise / Cruise Opposite	2	4	-75%
Cruise / Cruise Crossing	29	47	-62%

EUROFRA 2024

Type of conflict	Initial	Free route	Free route conflict Improvement (%)
Evolving / Evolving Parallel	7	6	11%
Evolving / Evolving Opposite	1	1	2%
Evolving / Evolving Crossing	2	4	-71%
Evolving / Cruise Parallel	16	7	57%
Evolving / Cruise Opposite	8	6	29%
Evolving / Cruise Crossing	17	20	-17%
Cruise / Cruise Parallel	18	8	54%
Cruise / Cruise Opposite	2	3	-30%
Cruise / Cruise Crossing	28	46	-61%

2012			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	10	10	0%
Evolving / Cruise	43	35	8%
Cruise/ Cruise	47	55	-8%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	43	24	43%
Opposite	10	11	-3%
Crossing	47	65	-38%

2018			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	9	9	1%
Evolving / Cruise	43	33	23%
Cruise/ Cruise	48	58	-21%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	40	20	50%
Opposite	11	10	5%
Crossing	49	69	-42%

2024			
Type of conflict	Initial	Free route	**Free route conflict Improvement (%)**
Evolving / Evolving	10	10	-8%
Evolving / Cruise	42	33	21%
Cruise/ Cruise	49	57	-17%
Type of conflict	**Free route conflict Improvement (%)**		
Parallel	41	21	48%
Opposite	12	10	16%
Crossing	47	69	-46%

- COMPLEXITY RESULTS – NEFRA

Initial Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2879	0,06615	0,00941	0,03091	0,00672
Day 2	2782	0,05978	0,00861	0,02739	0,00594
Day 3	2888	0,07106	0,00977	0,03220	0,00791
Day 4	2902	0,06292	0,00925	0,02876	0,00630
Day 5	3002	0,06880	0,00937	0,03228	0,00621
Day 6	2265	0,06198	0,00656	0,02977	0,00525
Day 7	2707	0,06740	0,00810	0,03179	0,00630

Free routed Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2879	0,06275	0,00748	0,03255	0,00638
Day 2	2782	0,05739	0,00678	0,02873	0,00594
Day 3	2888	0,06753	0,00781	0,03368	0,00779
Day 4	2902	0,06120	0,00719	0,03051	0,00602
Day 5	3002	0,06509	0,00754	0,03377	0,00624
Day 6	2265	0,06166	0,00556	0,03307	0,00531
Day 7	2707	0,06390	0,00627	0,03378	0,00585

Initial Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	3337	0,07195	0,00957	0,03496	0,01400
Day 2	3239	0,06710	0,00974	0,03356	0,00997
Day 3	3268	0,06371	0,00904	0,02837	0,00781
Day 4	3365	0,06573	0,00966	0,03311	0,00991
Day 5	3432	0,06873	0,00958	0,03535	0,01012
Day 6	2772	0,06368	0,00756	0,03203	0,00685
Day 7	3272	0,06748	0,00933	0,03484	0,00900

Free routed Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	3337	0,07153	0,00754	0,03733	0,00636
Day 2	3239	0,06810	0,00783	0,03703	0,00571
Day 3	3268	0,06649	0,00825	0,03529	0,00473
Day 4	3365	0,06558	0,00773	0,03457	0,00607
Day 5	3432	0,06696	0,00770	0,03644	0,00542
Day 6	2772	0,06295	0,00603	0,03375	0,00406
Day 7	3272	0,06740	0,00759	0,03650	0,00477

Initial Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	3986	0,09247	0,01059	0,03947	0,01004
Day 2	3954	0,09349	0,01027	0,03661	0,01539
Day 3	3844	0,08746	0,01058	0,03496	0,01136
Day 4	3853	0,08671	0,01034	0,03424	0,00934
Day 5	4022	0,08915	0,01074	0,03430	0,01111
Day 6	4120	0,09115	0,01044	0,03709	0,01206
Day 7	3452	0,08891	0,00828	0,03403	0,00787

Free routed Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	3986	0,08934	0,00739	0,04051	0,00370
Day 2	3954	0,09294	0,00748	0,03902	0,00582
Day 3	3844	0,08800	0,00785	0,03807	0,00526
Day 4	3853	0,08652	0,00783	0,03606	0,00413
Day 5	4022	0,08833	0,00796	0,03608	0,00620
Day 6	4120	0,08891	0,00753	0,03814	0,00514
Day 7	3452	0,08843	0,00600	0,03639	0,00364

Complexity NEFRA Summary

Year	AD Improvement	AD Improvement (%)	Vertical (Initial-FRA)	Vertical Improvement (%)	Horizontal (Initial-FRA)	Horizontal Improvement (%)
2012	0,0027	3,99%	0,002	20%	-0,0018	-6%
2018	-9,15E-05	-0,17%	0,002	18%	-0,0026	-8%
2024	0,00098167	0,10%	0,0025	24%	-0,0025	-7%

Year	Speed (Initial-FRA)	Speed Improvement (%)	Structural Index Improvement	Structural Index Improvement (%)	Complexity Score Improvement	Complexity Score Improvement (%)
2012	0,00016	2%	-0,0281	-4%	7,82E-05	0,09%
2018	0,00436	44%	0,0504	6%	3,38E-03	6,09%
2024	0,00618	54%	0,0631	10%	0,00619362	10%

COMPLEXITY RESULTS – SW FAB

Initial Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	1402	0,05864	0,32403	0,11183	0,05683
Day 2	1386	0,06016	0,32448	0,10940	0,04864
Day 3	1396	0,06451	0,34577	0,12548	0,04428
Day 4	1448	0,06333	0,37843	0,12826	0,05975
Day 5	1493	0,06610	0,38077	0,11349	0,05091
Day 6	1569	0,08137	0,45478	0,14976	0,05756
Day 7	1517	0,07470	0,41003	0,14291	0,05931

Free routed Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	1402	0,08058	0,73333	0,21107	0,08472
Day 2	1386	0,09509	0,72418	0,24595	0,08726
Day 3	1396	0,10749	0,72358	0,26248	0,08261
Day 4	1448	0,10009	0,75801	0,27900	0,13744
Day 5	1493	0,08784	0,66014	0,22966	0,10916
Day 6	1569	0,09664	0,75795	0,25607	0,14207
Day 7	1517	0,09364	0,82510	0,29156	0,12336

Initial Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2164	0,13120	1,3290	0,4475	0,2483
Day 2	1945	0,12665	1,2149	0,3877	0,2106
Day 3	1937	0,12229	1,0636	0,3710	0,1296
Day 4	2025	0,12856	1,0090	0,3619	0,1160
Day 5	2143	0,13519	1,1762	0,4359	0,2260
Day 6	2136	0,11782	1,0330	0,3524	0,1634
Day 7	2180	0,13390	1,2061	0,4099	0,2182

Free routed Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2164	0,05922	0,41100	0,07585	0,04882
Day 2	1945	0,05922	0,36642	0,06616	0,03507
Day 3	1937	0,06710	0,44561	0,07733	0,03272
Day 4	2025	0,06187	0,42998	0,08044	0,04673
Day 5	2143	0,06360	0,40905	0,07191	0,04090
Day 6	2136	0,07911	0,50159	0,09259	0,04089
Day 7	2180	0,07250	0,47117	0,09058	0,04229

Initial Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2942	0,10010	0,91857	0,13368	0,02842
Day 2	2731	0,09312	0,78749	0,12006	0,01790
Day 3	2468	0,10679	0,80311	0,12282	0,01564
Day 4	2466	0,10678	0,96662	0,13539	0,02707
Day 5	2566	0,09332	0,77531	0,11188	0,03741
Day 6	2705	0,09987	0,86933	0,13595	0,02297
Day 7	2713	0,09904	1,02314	0,14852	0,04365

Free routed Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	2942	0,13659	1,60899	0,27389	0,06016
Day 2	2731	0,13191	1,41371	0,21620	0,03962
Day 3	2468	0,12655	1,22811	0,20476	0,02328
Day 4	2466	0,13945	1,25337	0,20001	0,02140
Day 5	2566	0,14255	1,38077	0,20770	0,03976

Day 6	2705	0,12482	1,21272	0,18544	0,05832
Day 7	2713	0,13722	1,38968	0,22882	0,03209

Complexity SW FAB Summary

Year	AD Improvement	AD Improvement (%)	Vertical (Initial-FRA)	Vertical Improvement (%)	Horizontal (Initial-FRA)	Horizontal Improvement (%)
2012	0,000996879	1%	0,002	37%	-0,003	-16%
2018	-0,00562123	-6%	0,006	62%	-0,005	-19%
2024	-0,006103374	-5%	0,005	44%	-0,006	-20%

Year	Speed (Initial-FRA)	Speed Improvement (%)	Structural Index Improvement	Structural Index Improvement (%)	Complexity Score Improvement	Complexity Score Improvement (%)
2012	0,001	24%	0,01000	2,78%	0,0002	1%
2018	0,003	75%	0,050	12%	0,00195	5%
2024	0,004	79%	0,050	13%	0,00267	6%

COMPLEXITY RESULTS – EUROFRA

Initial Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	20179	0,14974	0,02113	0,05866	0,01134
Day 2	19342	0,14221	0,01996	0,05526	0,01080
Day 3	19812	0,14445	0,02074	0,05684	0,01147
Day 4	20225	0,14200	0,02007	0,05715	0,01174
Day 5	20699	0,14913	0,02093	0,05983	0,01130
Day 6	18901	0,15824	0,01941	0,06228	0,00925
Day 7	20119	0,14869	0,01964	0,05895	0,00987

Free routed Traffic 2012

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	20179	0,10864	0,01394	0,06431	0,00890
Day 2	19342	0,10337	0,01340	0,06103	0,00833
Day 3	19812	0,10619	0,01359	0,06318	0,00901
Day 4	20225	0,10610	0,01347	0,06353	0,00925
Day 5	20699	0,11198	0,01403	0,06697	0,00916
Day 6	18901	0,11895	0,01252	0,07064	0,00723
Day 7	20119	0,11321	0,01295	0,06727	0,00821

Initial Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	25436	0,18637	0,02486	0,07895	0,00075
Day 2	24291	0,17818	0,02397	0,07555	0,01384
Day 3	24543	0,17926	0,02446	0,07541	0,01573
Day 4	25114	0,18506	0,02531	0,07796	0,01657
Day 5	25844	0,18814	0,02550	0,07959	0,01644
Day 6	23833	0,19509	0,02331	0,08190	0,01418
Day 7	25388	0,18920	0,02431	0,08064	0,01561

Free routed Traffic 2018

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	25436	0,13885	0,01545	0,08632	0,00873
Day 2	24291	0,13191	0,01487	0,08320	0,00772
Day 3	24543	0,13349	0,01499	0,08290	0,00792
Day 4	25114	0,13653	0,01527	0,08586	0,00869
Day 5	25844	0,14103	0,01559	0,08879	0,00821
Day 6	23833	0,14933	0,01441	0,09362	0,00731
Day 7	25388	0,14367	0,01511	0,09039	0,00855

Initial Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	33066	0,25440	0,02991	0,10367	0,01979
Day 2	32098	0,25191	0,03054	0,09991	0,02065
Day 3	30653	0,24132	0,02942	0,09513	0,01676
Day 4	30967	0,24344	0,03002	0,09521	0,01932
Day 5	31815	0,25076	0,03105	0,09867	0,01996
Day 6	32725	0,25413	0,03133	0,10049	0,02020
Day 7	30725	0,26520	0,02921	0,10475	0,01711

Free routed Traffic 2024

Day	Number of flights	AD	HDIF	VDIF	SDIF
Day 1	33066	0,19428	0,01857	0,11376	0,01055
Day 2	32098	0,18808	0,01866	0,10795	0,01042
Day 3	30653	0,17885	0,01796	0,10352	0,00955
Day 4	30967	0,18072	0,01804	0,10301	0,00967
Day 5	31815	0,18549	0,01840	0,10710	0,01062
Day 6	32725	0,19033	0,01877	0,11049	0,01004
Day 7	30725	0,20294	0,01776	0,11780	0,00887

Complexity EUROFRA Summary

Year	AD Improvement	AD Improvement (%)	Vertical (Initial-FRA)	Vertical Improvement (%)	Horizontal (Initial-FRA)	Horizontal Improvement (%)
2012	0,038001177	25,71%	0,006855406	34%	-0,00684972	-12%
2018	4,66E-02	25,09%	0,009428507	38%	-0,008725873	-11%
2024	0,062923462	25,01%	0,011899965	39%	-0,009399819	-9%

Year	Speed (Initial-FRA)	Speed Improvement (%)	Structural Index Improvement	Structural Index Improvement (%)	Complexity Score Improvement	Complexity Score Improvement (%)
2012	0,00223903	21%	0,002244712	3%	0,002	3%
2018	0,00514321	39%	0,005845843	5%	0,006	5%
2024	0,009152844	48%	0,011652989	8%	0,012	8%

11 APPENDIX B – Simulation Process

Annex Simulation Scheme