Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

FINAL DEGREE THESIS

TITLE: The impact of the implementation of Free Flow in the European Airspace

DEGREE: Aeronavigation engineering

AUTHOR: Biel Mas Verdú

DIRECTOR: Hector Fornés

DATE: July 7, 2023

Títol: L’impacte de la implementació del Free Flow a l’espai aeri Europeu

Autor: Biel Mas Verdú

Director: Héctor Fornés

Data: 7 de juliol del 2023

Resum

Aquest projecte té com a finalitat investigar l'impacte de la implementació de la tècnica coneguda com a "Free Flow" a l'espai aeri durant un període de cinc anys, del 2015 al 2020. Es realitza un estudi comparatiu de dues rutes aèries amb característiques diferents: Barcelona-Sevilla i Barcelona-Dublín. L'anàlisi es centra en l'eficiència dels vols i busca establir una relació amb el Free Flow.

El Free Flow és una tècnica que permet als pilots volar amb major llibertat després d'obtenir l'aprovació prèvia dels controladors aeris. A Europa, Eurocontrol és l'organisme responsable de supervisar el desenvolupament i garantir el funcionament d'aquesta tècnica. Actualment, es troba en procés d'implementació i es preveu que hi haurà una millora considerable cap al 2030.

Mitjançant dades proporcionades per Eurocontrol i un conjunt de codis de programació a MATLAB, es calcularan els quilograms de combustible estalviats per cada ruta a partir de la diferència de distància volada respecte la planejada. Per la ruta de Barcelona a Dublín també es farà una estimació de les emissions de CO2 i altres partícules contaminants relacionades amb la diferència de distància esmentada. Finalment, es farà un càlcul en termes de diners que s’estalviarà Ryanair a través de les millores d’eficiència de la ruta Barcelona – Dublín. A través de la xifra de diners obtinguda, es trauran unes conclusions generals pels beneficis de les aerolínies.

Cal destacar que els resultats de l'estudi poden estar afectats per la pandèmia de la SARS-CoV-19, la qual va causar pertorbacions significatives en el sector aeri durant l’any 2020. No obstant això, els resultats obtinguts semblen molt rellevants en un context on les emissions són el principal factor per millorar la sostenibilitat del transport aeri.

Paraules clau: Free Flow, espai aeri, capacitat, combustible, GCD, ATM

Title: The impact of the implementation of Free Flow in the European Airspace

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Overview

This project aims to investigate the impact of the implementation of the technique known as "Free Flow" in airspace over a period of five years, from 2015 to 2020. A comparative study of two air routes with different characteristics: Barcelona-Seville and Barcelona-Dublin. The analysis focuses on flight efficiency and seeks to establish a relationship with Free Flow.

Free Flow is a technique that allows pilots to fly more freely after obtaining prior approval from air traffic controllers. In Europe, Eurocontrol is the body responsible for overseeing the development and guaranteeing the operation of this technique. Currently, it is in the process of implementation, and it is expected that there will be a considerable improvement towards 2030.

Using data provided by Eurocontrol and a set of programming codes in MATLAB, the kilograms of fuel saved for each route will be calculated based on the difference between the distance flown and the planned one. For the route from Barcelona to Dublin, an estimate will also be made of CO2 emissions and other polluting particles related to the difference in distance mentioned. Finally, a calculation will be made in terms of money that Ryanair will save through the efficiency improvements on the Barcelona - Dublin route. Through the figure of money obtained, some general conclusions will be drawn for the benefits of the airlines.

It should be noted that the results of the study may be affected by the SARS-CoV-19 pandemic, which caused significant disruptions in the air sector during 2020. However, the results obtained seem very relevant in a context where emissions are the main factor to improve the sustainability of air transport.

Keywords: Free Flow, airspace, capacity, fuel, GCD, ATM

AGRAIMENTS

Aquest projecte va dedicat per a totes aquelles persones que m’han fet costat durant aquests últims 4 anys. Amics, companys, professors, però sobretot, els meus pares i al meu germà, que sempre hi han sigut i sempre hi seran.

Agrair també a l’Hector, tutor d’aquest projecte, pel constant suport que m’ha ofert.

Gràcies Marc per la trucada que vam poder tenir i per la informació que em vas poder aportar.

S’acaba una etapa molt bonica, i en comença una altra de ben diferent, a per totes!

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SESAR: Single European Sky ATM Research
ATM: Air Traffic Management
ICAO: International Civil Aviation Organization
EU: European Union
ATC: Air Traffic Control
FRA: Free Route Airspace
TRA: Temporary Reserved Area
TSA: Temporary Segregated Area
FIR: Flight Information Region
VOR: Very High Frequency Omni-Directional Range
UPR: User Preferred Routing
AU: Airspace User
SES: Single European Sky
FRAM: Functional Resonance Analysis Method
ANSP: Air Navigation Service Provider
FAA: Federal Aviation Administration
RTCA: Radio Technical Commission for Aeronautics
NATS: NATIONAL AIR TRAFFIC SERVICES
TCAS: Traffic Alert and Collision Avoidance System
ATS: Air Traffic Service
UIR: Upper Information Region
MTCD: Medium-Term Conflict Detection
TTM: Tactical Trajectory Management
CNS: Communications, Navigation and Surveillance
PBN: Performance-Based Navigation
HFE: Horizontal Flight Efficiency
KEP: Key Performance environment based on filed flight Plan
KEA: Key Performance environment based on Actual trajectory
KES: Key Performance environment based on the Shortest route available for flight planning
GCD: Great Circle Distance
NM: Nautical Mille
ADS-B: Automatic Dependent Surveillance-Broadcast
LEBL: Barcelona
LEZL: Sevilla
EIDW: Dublin
VLG: Vueling
RYR : Ryanair
MLAT: Multilateration System
GAT: General Air Traffic
IFR: Instrumental Flight Rules
MTOW: Maximum Take-Off Weight
TDOA: Time Difference Of Arrival
ADEP: Departure Airport
ADES: Destination Airport
AC: Aircraft
PAX: Passenger

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INTRODUCTION

Air travel revolutionized transportation after World War II, offering faster and safer journeys. However, the COVID-19 pandemic caused a significant decline in passenger numbers, reminiscent of the 1970s. As passenger volumes gradually recover, the aviation sector benefits. Concerns regarding airspace capacity and environmental impact prompted studies, leading to the development of solutions such as the Free Flow flight procedure. This approach optimizes fuel consumption, reduces emissions, saves time, and lowers costs.

Free Flow operations under the concept of Free Route Airspace allow pilots to navigate freely between designated points with prior authorization from air traffic control (ATC). This enhances flight efficiency, reduces environmental impact, and aligns with sustainability goals in the aviation industry, resulting in cost savings.

This project focuses primarily on the concept of Free Flow. The first part of the study provides a comprehensive explanation of the theoretical background of this technique. It covers aspects such as its definition, the process of its implementation, and the expected functionality in the future. This section aims to establish a solid understanding of Free Flow and its significance in optimizing air traffic management.

The second part of the project delves into the parameters that define the efficiency of a flight. These parameters are carefully defined and explained to provide a clear understanding of their role in assessing flight performance. By elucidating these parameters, the project aims to facilitate the comprehension of the case study results and their implications in evaluating the effectiveness of Free Flow operations.

To bridge the theory from the first part to flight efficiency, two flights are analysed. The Barcelona – Sevilla route showcases the Spanish airspace, while the Barcelona – Dublin route provides valuable insights into the European airspace, given its longer distance and the presence of an annually upgraded Free Route Airspace (FRA).

The primary focus of this study is to compare the filed route with the actual flown route, with the intention of demonstrating the greater efficiency of the latter. The actual flown route considers various factors, including the implementation of Free Flow, which is expected to contribute to improved efficiency.

In the final part of the project, the discrepancy between the filed route and the actual route is considered, specifically in terms of distance. Based on this difference, estimations are made for fuel consumption, as well as the emissions of CO_2 and other pollutants. These calculations provide insights into the potential environmental benefits associated with the implementation of more efficient flight routes, such as those facilitated by Free Flow.

CHAPTER 1. FREE FLOW

1.1. Single European Sky ATM Research (SESAR)

With the continuous growth of air traffic worldwide, the existing Air Traffic Management (ATM) equipment and methods may not be able to handle the increasing number of flights and operations efficiently. The Single European Sky ATM Research (SESAR) program [1] is an initiative launched by the European Union to develop and implement new technological solutions to modernize and improve the ATM system and infrastructure.

The SESAR program aims to achieve several objectives, including enhancing safety, improving capacity and efficiency, reducing the environmental impact of aviation, and ensuring interoperability and harmonization of ATM systems across Europe. The program's activities are aligned with the Global Air Navigation Plan of the International Civil Aviation Organization (ICAO), which provides a framework for the development of the global air navigation system [2].

Through the SESAR program, new concepts and technologies are being developed, validated, and implemented to enhance the performance of the ATM system, such as the integration of new technologies like satellite-based navigation and communication, automation of air traffic control, and improved information sharing between stakeholders. By doing so, SESAR aims to meet the growing demands of the aviation industry while ensuring safety and minimizing the environmental impact of air travel.
The aim of this project is to focus on the development of one of the solutions implemented by SESAR, which is the Free Flow Airspace.

1.2. Free Route Airspace concept

It has been demonstrated that air routes in Europe were not optimally designed. In 2009 a flight's route was on average 47.6 km (or 5.4%) too long compared to its optimum flight trajectory, which means more flight and engine running time with more fuel burn and emissions [3].

The routes were longer due to several factors, as:

- Sub-optimal airspace design
- Inefficient city pairs
- Constraints related to need for civil and military airspace users to share airspace
- Inappropriate flight planning
- Inappropriate route utilization
- Route restrictions

Since 2012, the EU-wide performance targets agreed, under the Single European Sky, that the legislation will provide a formal framework for the development of safer and more efficient European airspace, with straighter and shorter routes.

There was when the first Free Route Airspace was introduced.

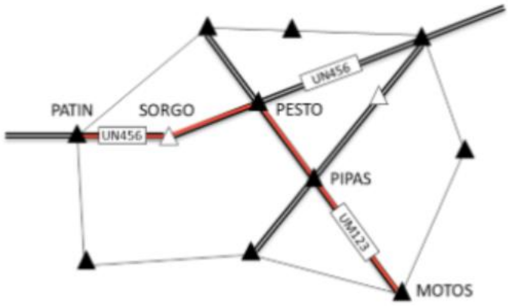

Fig 1.1 Traditional flight track sample

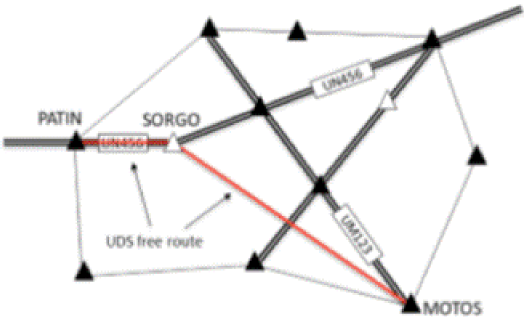

Fig 1.2 Free route track sample

It is only applicable during flight planning phase. After a flight plan has been filed and approved, the operation is subject to its approved flight plan and, when applicable, to ATC clearances.

Within this airspace, flights always remain subject to air traffic control and to any overriding airspace restrictions.

1.2.1. Description

Free route airspace (FRA) [4] is a concept of providing air traffic services in which an operator can choose their route subject to only a few limitations (e.g. fixed entry and exit points and the need to avoid danger areas, TRAs or TSAs) as opposed to the situation where standard airways should be used. In most cases the straight line between an entry point and an exit point will be chosen. If for some reason this is not appropriate (e.g. a danger area needs to be avoided) additional turning points can be specified. These can be navigational aids, published navigational points or points with specified coordinates. The following diagram gives an overview of the main FRA rules:

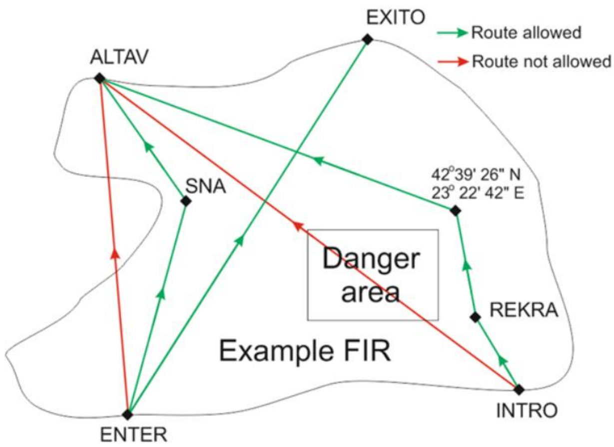

Fig 1.3 Diagram of the main FRA rules [4]

Example of allowed and not allowed FRA routes to be considered during the pre-flight planning.

In the example FIR depicted, INTRO and ENTER are entry points, ALTAV and EXITO are exit points, SNA is a VOR and REKRA is an RNAV point. When FRA is implemented, the green routes would be accepted and the red routes would be rejected by the ATC flight plan processing system. The reasons for rejection include the crossing of a danger area (INTRO-ALTAV) and the requested route not remaining within the FRA (ENTER-ALTAV). The approved routes can be either direct from an entry to an exit point (e.g. ENTER-EXITO) or with intermediate points (navigational aids (SNA), published points (REKRA) or randomly selected points (42°39'26" N, 23°22'42" E)).

This kind of flight was first used in Oceanic flights. Then started to be implemented at continental level in 2 stages:

- 1st stage: more direct routes not based on fixed airspace structure.
- 2nd stage: consider UPRs.

User Preferred Routing (UPR), in which Airspace User (AU) can define routes with at least a significant part not defined according to published route segments but specified by the AU.

UPR has not to be necessarily a direct route between entry and exit points of a specific airspace, but it's expected that the flight is executed along direct segments between any waypoint published and/or specified by the AU.

It also allows AU to adapt routes in finer detail on a day-by-day basis to optimize against wind, ATC charges etc. to meet business requirements.

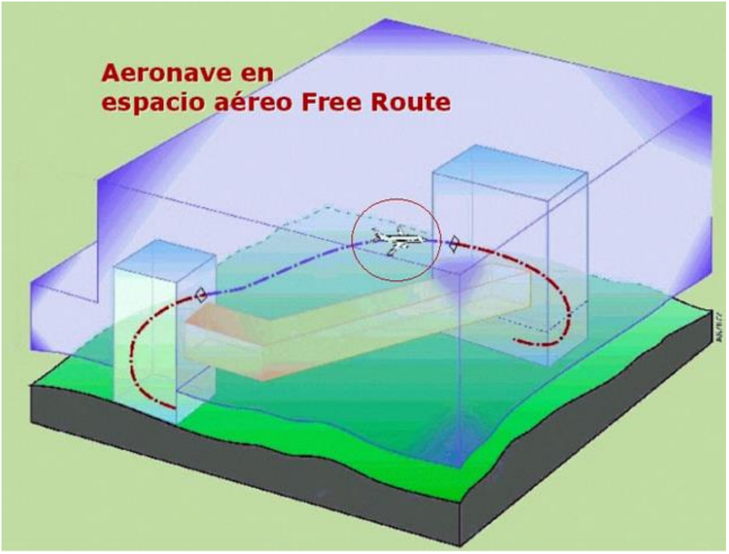

Fig 1.4 Airplane in a Free route airspace [5]

The implementation of FRA was obviously created to provide advantages. But as everything it has several disadvantages:

Table 1 List of advantages and disadvantages of FRA

ADVANTAGES	DISADVANTAGES
- Reduction of flight length - Reduction of fuel consumption - Reduction of CO2 emissions - Reduction of flight time	- Traffic less structured - Interoperability between actors, such as military and civil, more difficult - Potential reduction of capacity - Need of interstate coordination

1.2.3. Implementation types and deployment

Free route operations can be:

- Time limited (e.g. at night) – this is usually a transitional step that facilitates early implementation and allows field evaluation of the FRA while minimising the safety risks.
- Structurally or geographically limited (e.g. restricting entry or exit points for certain traffic flows, applicable within CTAs or upper airspace only) – this could be done in complex airspaces where full implementation could have a negative impact on capacity.

- Implemented in a Functional Airspace Block environment – a further stage in the implementation of FRA. The operators should treat the FAB as one large FIR.
  - Within SES airspace – this is the ultimate goal of FRA deployment in Europe.

Extension of FRA: User Preferred Routing (UPR), in which Airspace User (AU) can define routes with at least a significant part not defined according to published route segments but specified by the AU.

UPR not necessarily a direct route between entry and exit points of a specific airspace, but it’s expected that the flight is executed along direct segments between any waypoint published and/or specified by the AU.

Allows AU to adapt routes in finer detail on a day-by-day basis to optimize against wind, ATC charges etc. to meet business requirements.

1.2.4. Free Route Airspace Maastricht (FRAM) and Karlsruhe

Between June 2012 and May 2014, the Free Route Airspace Maastricht and Karlsruhe (FRAMaK) project [6] - funded by the SESAR Joint Undertaking - conducted live trials to demonstrate cross-border free route airspace capabilities in complex, high-density airspace with positive results. The demonstration concluded that airspace users can save up to four nautical miles per flight as a result of the cross-border direct routings.

Since March 2011, 142 new direct routes available in airspace controlled by MUAC (upper air space of Belgium, Germany, Luxembourg and the Netherlands) controlled by EUROCONTROL Maastricht ACC.

The implementation of this concept was gradual year by year:

- March 2011: during the least busy hours of the night, 00:00 to 06:00 CET
- June 2011: extended night-time, from 00:00 to 08:00 CET
- End of 2011: weekends, from Saturdays 00:00 to Mondays 08:00 CET
- 2012: day-time on busy Fridays (from 12:00 CET to Monday 08:00 CET) and during national holidays
- 2013+: 24/7 operations. Full concept of user-preferred trajectories

The savings expected from 1st phase of FRAMaK deployment during nights and weekends estimated at:

- 1.16 million km per year (equivalent to 29 flights around the world)
- 3,700 t of kerosene
- 12,000 t of CO_2
- 37 t of NO_x

After the successful results of the first phase deployments, it continued as follows:

- End of 2017: 51 ACCs partially or fully implemented FRA
- By 2019/2020, additional savings of between 60,000-75,000 NM a day can be expected, with subsequent fuel, environment and cost benefits.
- By end of 2019, most European airspace was expected to have implemented FRA, with all airspace having this type of operations by 2021/2022.

This progress is result of very close cooperation between Network Manager, ANSPs, military partners and air space users.

Cross-border implementation started and already applicable, or will be soon, in many parts of Europe, namely Austria-Slovenia, Romania-Hungary-Bulgaria, Belgrade-Zagreb ACCs, MALTA-ITALY, Estonia-Latvia-Finland-Sweden-Denmark-Norway.

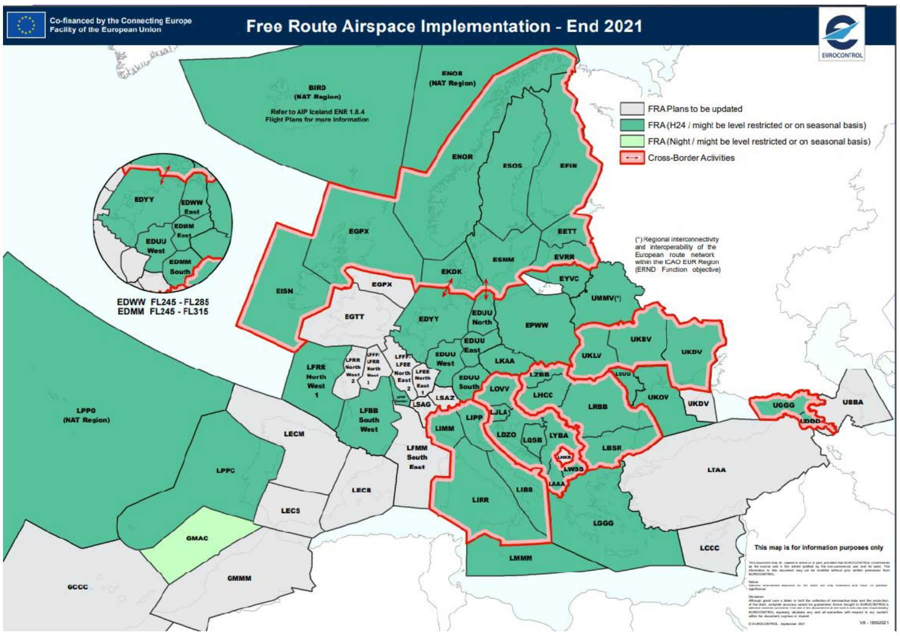

Fig 1.5 Free Route Airspace Implementation - End 2021 [6]

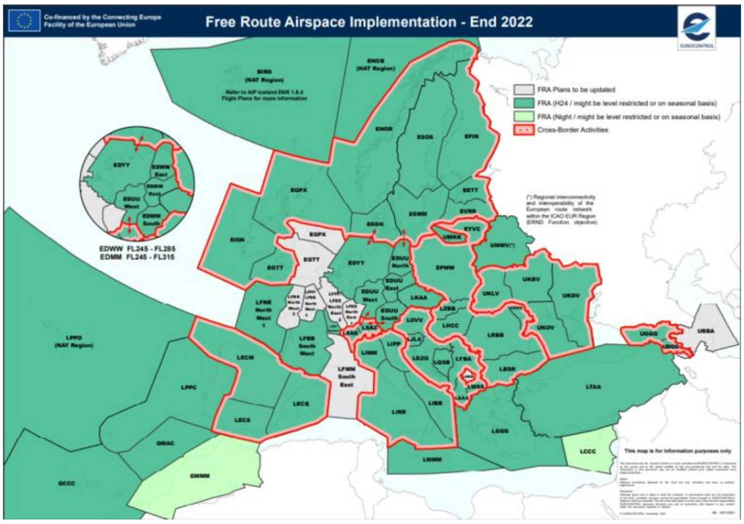

Fig 1.6 Free Route Airspace Implementation - End 2022 [6]

As seen in these images, almost all Europe is now under Free Route Airspace, except the south-east and north of France and the southern part of England.

1.2.5. Projection charts for the coming years

Eurocontrol has defined the projection charts for the coming years up to 2030 [7]. The aim is to give a little more coverage year after year.

In these two images, the projection chart by the end of 2030 can be compared to the projection chart by the end of 2023:

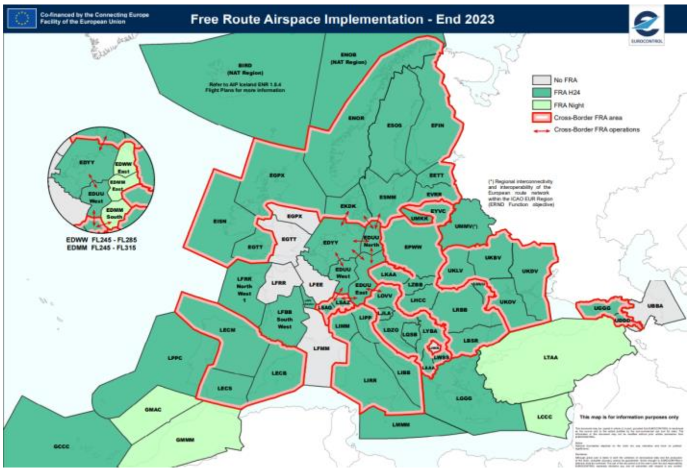

Fig 1.7 Free Route Airspace Implementation - End 2023 [7]

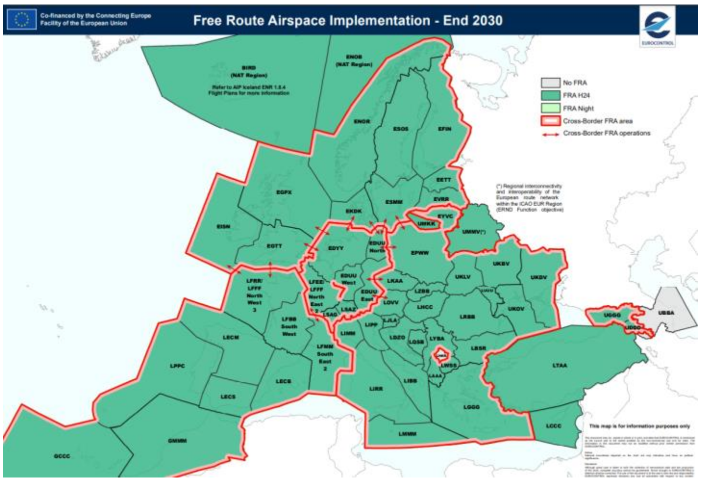

Fig 1.8 Free Route Airspace Implementation - End 2030 [7]

The statement suggests that Eurocontrol envisions a gradual progression towards FRA implementation. Each year, as new territories are covered and adopt FRA, improvements can be observed in terms of airspace efficiency and capacity. This implies that the implementation of FRA is a step-by-step process, where the benefits and advancements are expected to accumulate over time. It is expected to be finished by the end of 2030. However, despite the year-by-year improvements, the statement suggests that the complete implementation of FRA by 2030 may not be achievable. It implies that the timeline for achieving full implementation could extend beyond 2030. This could be due to the complexity of the implementation process, which involves coordination among multiple stakeholders, infrastructure upgrades, regulatory considerations, and safety assessments.

1.3. Free Flight concept

1.3.1. Description

In 1993, Bill Cotton [5], a United Airlines pilot, presented a concept called "Free Flight" to the FAA, aimed at eliminating restrictions on the inefficient North American air traffic management system to accommodate more air traffic.

The FAA requested a study by the Radio Technical Commission for Aeronautics (RTCA) to evaluate the feasibility of the proposal. The resulting report emphasized the need to change the focus of the Free Flight concept, prioritizing medium-term planning over freedom in the short term.

Free Flight was defined as the ability to operate safely and efficiently under instrument flight rules where pilots have the freedom to select their route and speed in real-time without needing to contact the ATC.

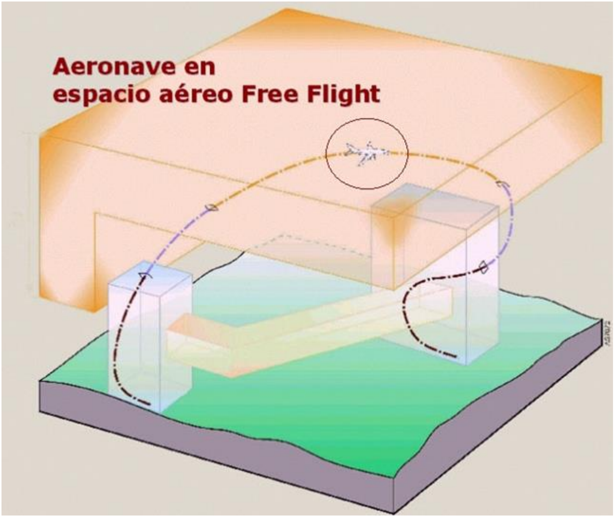

Fig 1.9 Airplane in a Free Flight airspace [5]

The report also discussed operational concepts such as dynamic sectorization of airspace, collaborative decision-making, and auto-separation of aircraft. The Free Flight concept aims to optimize aircraft routing, speed, and altitude considering weather conditions without requiring specific ATC authorization. It also would allow aircraft to fly more fuel-efficient routes with optimal profiles, potentially saving millions of dollars each year.

Continuous profiles can achieve around 11% (short-haul flights) and 6% (medium-haul flights) of fuel savings, i.e., between 220 and 380 [kg], and the corresponding CO_2 emissions when compared to current operations.
Other research showed that continuous cruise phase can lead to fuel savings between 1% and 2% of total trip fuel for an Airbus A320. It also reduces trip time between 1% and 5%.

1.3.2. Implementation types and deployment

Based on who is responsible for the separation of aircraft, three implementation models of the concept have been identified to "liberalize" air navigation:

- Control-based model (without delegation)
- Cabin-based model (total delegation)
- Shared model (partial delegation)

➢ CONTROL-BASED MODEL

Basically, it is the current operational scheme evolved according to what the English provider of air traffic services, NATS (National Air Traffic Services), identified during a series of simulations, such as the need for a new element in the ATC's work scheme: a multi-sector planner who supervises the medium-term demand of a set of sectors. It was called a multi-sector planner, and its mission would be to distribute traffic and solve conflicts 20 or 30 minutes before flights enter the first of the sectors involved in their respective routes.

- CABIN-BASED MODEL

Also known as "Autonomous Operation," it involves total delegation in the flight deck of the responsibility for conflict detection and resolution for aircraft equipped with appropriate navigation, surveillance, and self-protection systems while operating in airspace designated for Free Flight operations [self-protection means that the aircraft would be equipped with devices whose principle of operation would be based on the existence of two areas around the aircraft, the "protection" and "alert" areas, which is known as TCAS or an evolution of it].

- SHARED MODEL

The aim of partial delegation is to allow greater flexibility in the use of available airspace. To achieve this, operational responsibility for separation during specific manoeuvres is transferred to the aircraft, reducing the workload of the ATC and increasing the system's capacity. With this model, the controller maintains the initiative and authority in managing the situation, but with the particularity that whoever is better situated to solve a conflict takes the measures aimed at carrying out separation with the involved aircraft. Obviously, we would be talking about a volume of controlled airspace, properly equipped aircraft, and defined rules for the case.

1.4. Free Flight & Free Route

This image is a hypothetical representation of how the Free Route and Free Flight would be combined above the ATS routing.

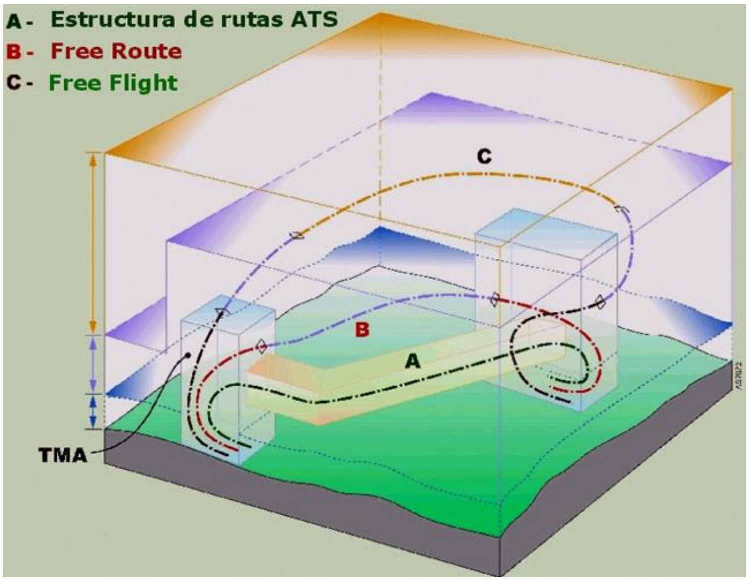

Fig 1.10 Free Route & Free Flight [5]

While Free Route focuses specifically on enabling aircraft to fly along more direct routes within predefined airspace, Free Flight encompasses a wider range of principles that promote pilot autonomy and decision-making throughout the entire flight process. Free Flight may involve advanced technologies, such as onboard systems and communication tools, to facilitate real-time information exchange between pilots and air traffic control.

In summary, Free Route is a specific implementation within the broader concept of Free Flight. Free Route aims to optimize airspace utilization by allowing aircraft to follow direct routes, while Free Flight encompasses a philosophy that empowers pilots with greater flexibility and decision-making authority in flight planning and execution.

1.5. Free Route Airspace in Spain

The HISPAFRA project [8] aims to implement the concept of free route airspace within Spain. At the European level, the FRA initiative is promoted and coordinated by Eurocontrol, in accordance with the stipulations of Commission Implementing Regulation (EU) 2021/116 of 1 February 2021. It is a nationwide project in which Ineco is supporting the ENAIRE Director of Operations and helping to coordinate all of the bodies involved, which include the General Directorate of Civil Aviation, the National Air Safety Agency, the Spanish Air Force and ENAIRE.

The implementation of HISPAFRA has been divided into different phases: in each phase the restrictions become more flexible and new functionalities are incorporated into the control system, while maintaining appropriate levels of capacity and safety. The European regulations stipulate that the initial phase must be implemented before 31 December 2022 and the final stage by December 2025, along with a cross-border element involving at least one other Member State. After this date, rollout of the FRA concept will continue and there will be greater cross-border implementation between Member States, thereby enabling a more flexible European airspace and more efficient planning on the part of airlines.

For phase 1 of HISPAFRA, two FRA cells [9] have been defined:

- Continental cell: Its boundary is that of the union of Madrid and Barcelona UIRs, between flight levels FL245 and FL660. It excludes the airspace volumes delegated by Spain to Portugal, and including the airspace volumes delegated by Portugal to Spain. Entry into service: December 2, 2021.

- Canarias cell: Its boundary is that of Canary Islands UIR, between flight levels FL305 and FL660. Entry into service: October 7, 2021.

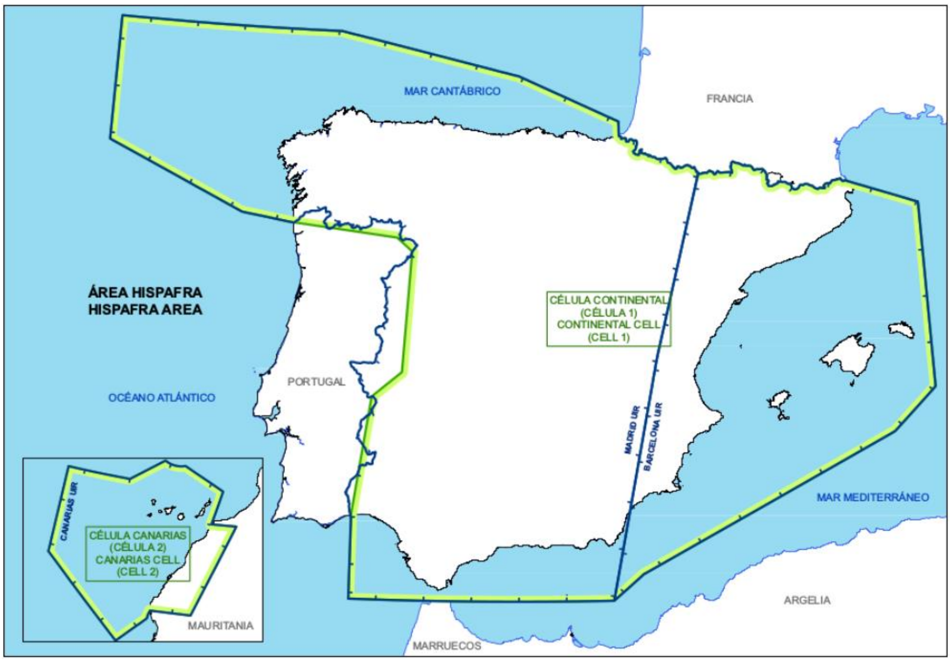

Fig 1.11 Two cells of the FRA in Spain [9]

Existing published routes will not be eliminated during this initial phase; rather, airspace users will have the additional option of drawing up FRA plans that make use of these existing routes. This will enable the transition towards a free route approach for all, without changing the way in which ATC operates and with the aim of maintaining the same levels of capacity and safety, while enabling users to gradually adapt their systems in preparation for the subsequent phases.

Looking ahead to these subsequent phases, in which free connection between a greater number of waypoints will gradually become more flexible, ENAIRE is developing and deploying a series of new functionalities for its ATC system. These functionalities enable controllers to determine, ahead of time and with increased precision, whether a particular flight level or direct route presents an air traffic risk, prior to granting ATC clearance for separation provision. Examples of the tools available include Medium-Term Conflict Detection (MTCD) and Tactical Trajectory Management (TTM).

As it will be explained later in this project, the case study will be from 2015 to 2020, so explaining different changes in the Spanish Airspace during this period will help to understand the results:

1. Airspace restructuring project: Between 2014 and 2020, a project to restructure the Spanish airspace was carried out with the aim of improving efficiency and capacity of air traffic. This included the implementation of new routes and navigation procedures, as well as the introduction of more advanced air traffic management technologies such as performance-based air traffic management (ATM/CNS) system.
2. Implementation of the Single European Sky: Spain has actively participated in the implementation of the Single European Sky, which aims to harmonize and optimize airspace across Europe. This involves coordination and cooperation among the member countries of the European Union to improve air traffic efficiency and reduce delays.
3. Opening of new control areas: To enhance air traffic management, new control areas have been established in the Spanish airspace. These control areas are designed to optimize traffic flow management and allow for greater flexibility in flight routes.
4. Introduction of new navigation procedures: New navigation procedures, such as performance-based navigation (PBN) procedures, have been implemented. PBN utilizes satellite navigation technology to optimize flight routes and reduce distances flown.

CHAPTER 2. HORIZONTAL FLIGHT EFFICIENCY

2.1. Description

The Horizontal Flight Efficiency (HFE) [10] is very generally speaking obtained by comparing the flight trajectory with the GCD. There are three indicators of flight efficiency used in Europe. They are called Key performance Environment indicators, based on filed flight Plan (KEP), based on Actual trajectory (KEA) and based on shortest route available for flight planning (KES). Each indicator has a different approach, addressed to different needs.

- KEP: It compares the GCD with the last filed flight plan.
- KES: The KES is obtained by comparing the GCD with the shortest constrained route available for flight planning.
- KEA: This indicator uses the real flight distance (the trajectory obtained with radar/surveillance data) with the GCD.

In this project, the focus will be on the KEA indicator, for which the greater the difference between the flight distance with respect that of the theoretical optimum, the lower the horizontal flight efficiency. KEP will also be computed, which will be compared with the KEA.

The viewpoint for both Eurocontrol and the ICAO in their HFE related studies is that to not assume local inefficiencies (e.g airport control airspace), this comparison must start, and later end, outside a 40 NM circumference from the route airports. The 40 NM value is determined to englobe most TMA operations. This way, all the different departure and approach procedures, that might be limited by obstacles, noise limitations, traffic, etc., are not considered, and only the “route” segment is analysed. Fig 4.1 exemplifies this casuistic.

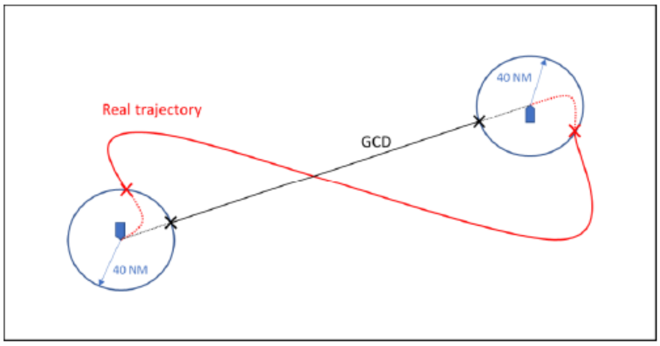

Fig 2.1 GCD illustration [10]

Only the segments comprised between the X markers (solid lines) are compared.

Here under, it will be computed the HFE of the flights according to the present definition, but also how much the HFE varies if the trajectory inside the 40 NM circumference is considered, to obtain an approximation of the inefficiencies induced near the airports.

HFE is computed as the subtraction between the theoretical 100% efficiency and the inefficiency found in that flight. Therefore,

$$HFE\,[\%] = 100 - HFI \tag{2.1}$$

Where:

$$HFI = \frac{L - H}{H}\,\% = \left(\frac{L}{H} - 1\right)\% \tag{2.2}$$

Where:

- L = Length of the trajectory (outside 40 NM ring)
- H = Length of direct course -GCD- (outside 40 NM ring)

In this study, the distance between consecutive 4D points is calculated using the Haversine equation. To determine the length of the trajectory (L), any pairs of points within a 40 NM radius are excluded. In an ideal scenario, once a point falls outside this radius, the flight distance would begin to accumulate. However, due to some inaccuracy found in the flight data used in this study, we will consider a fixed radius of 40 NM around each airport. Consequently, 80 NM will be subtracted from the total flight distance to account for the exclusion of these airport regions.

2.2. GCD and Haversine equation

The great-circle distance [11] is the shortest distance between two points on the surface of a sphere, measured along the surface of the sphere. The distance between two points in Euclidean space is the length of a straight line between them, but on the sphere, there are no straight lines. In spaces with curvature, straight lines are replaced by geodesics. Geodesics on the sphere are circles on the sphere whose centres coincide with the centre of the sphere and are called 'great circles'.

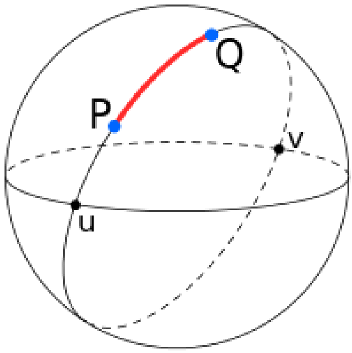

Fig 2.2 GCD between points P to Q

The fact that the Earth can be approximated to a sphere, enables the use of great circle distance calculations, with only an error of 0.5%. This was already discovered many centuries ago, and determined a concept still used today, great circle navigation, in where routes for both ships and aircrafts, are planned to try to always achieve the shortest distance.

The real flown distance is never equal to the GCD [12] (in fact it can be up to an average additional 5% in Europe) most studies about fuel consumptions and emissions rely on this ideal distance, perhaps adding some correctional values. On that account, this project will rely on a more accurate measurement for the real flight distance, that, while still depending on great circle formulas and still not being perfectly accurate due to small precision errors in the ADS-B measurements, has proven to be much more cognate to reality.

To find a more accurate flight distance, instead of applying the GCD between the departing and arriving airport from the Eurocontrol data, the Haversine equation [13] is used to compute the great circle distance between each of these data entries, following a linearization approach (see Fig 2.3). Please note that when using most conventional 2D maps, the GCD will mostly appear as a straight line.

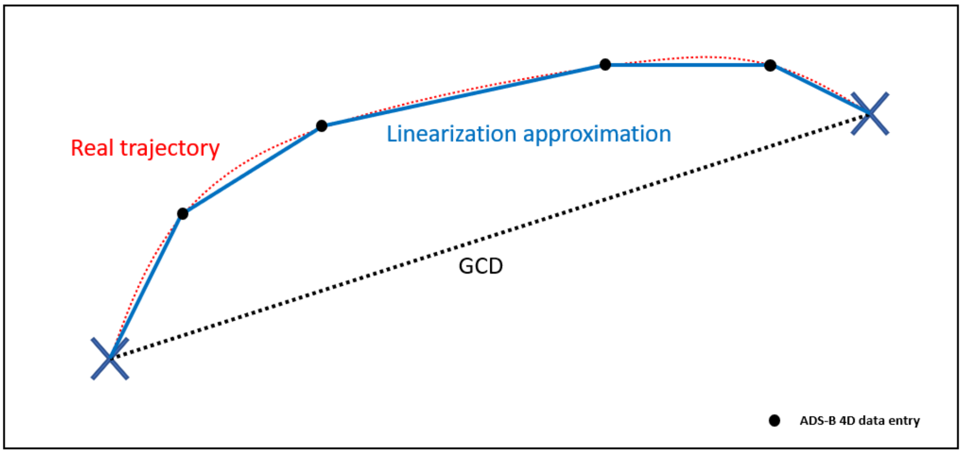

Fig 2.3 Real trajectory vs GCD [10]

While there are many methods to compute the GCD, the Haversine equation is better fitted to use for small distances, which fits perfectly with the methodology used. The Haversine equation to compute the great circle distance between two points (with decimal latitude and longitude) is as it follows:

$$d = 2R_T * \arcsin\left(\sqrt{sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1) * \cos(\varphi_2) * sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \quad \textbf{(2.3)}$$

Where:

- $\varphi 1$,$\varphi 2$ are the latitude of point 1 and latitude of point 2.
- $\lambda 1$,$\lambda 2$ are the longitude of point 1 and longitude of point 2.
- R_T is the radius of the Earth [14].

The Earth's radius is not uniform and varies based on its latitude and longitude. The equator has a radius of 6,378.137 kilometres, while the poles have a radius of 6,356.752 kilometres. Different conventions exist that determine which value to use depending on the investigation's purpose. For astronomical computations, the Nominal Polar Radius is used. However, for this project, the chosen radius of the Earth is the Arithmetic Mean Radius, which is approximately 6,371.0088 kilometres. This value is preferred because it results in more accurate calculations for distances using GCD formulas. It approximates the Earth as a sphere, minimizing the mean square relative error for distance calculations.

CHAPTER 3. CASE STUDY

3.1. Data collection

After defining the theoretical background, the next step was to obtain flight information. Various methodologies were evaluated, and the benefits and drawbacks of each were considered. Based on the ease of obtaining and classifying data, as well as the quantity and quality of flights, it was determined that the two best options to populate the model were the online application FlightRadar24 and the online data repository of Eurocontrol.

Eurocontrol is a trusted source of reliable and well-organized information for air traffic management in Europe. Their data collection processes involve collaboration with stakeholders and utilization of various sources, ensuring a comprehensive understanding of air traffic patterns. Eurocontrol's data adheres to high-quality standards and is widely used by airlines, airports, regulators, and researchers for decision-making and policy development. Overall, Eurocontrol's accurate and organized data contributes to enhancing safety, efficiency, and sustainability in European airspace.

For the case study, two scenarios were analysed. The flight from Barcelona (LEBL) to Sevilla (LEZL) operated by Vueling (VLG) was used to analyse the Spanish Airspace, while the flight from Barcelona (LEBL) to Dublin (EIDW) operated by Ryanair (RYR) was used to analyse the western part of the European Airspace.

3.1.1. Eurocontrol tracking principles

Eurocontrol uses a variety of radars to track flights in its airspace, including primary and secondary radars, ADS-B and multilateration radars (MLAT).
Flight tracking systems have been developed using surveillance methods, which allow both air traffic controllers and regular users to track aircraft positions in real-time and access recorded flight trajectories.

- PRIMARY SURVEILLANCE RADAR

Primary radars [15], also known as primary surveillance radars, send out radiofrequency pulses and measure the time it takes for the signal to bounce off the aircraft and return to the radar. From this, the radar can determine the position and speed of the aircraft. Primary radars are useful in areas where there are no onboard transponder systems in the aircraft.

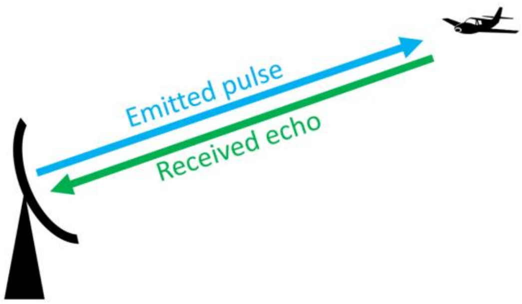

Fig 3.1 Primary Surveillance Radar [15]

- SECONDARY SURVEILLANCE RADAR

In the other hand, secondary radars [16], also known as secondary surveillance radars, function similarly to primary radars but also receive signals from transponders onboard the aircraft. These signals transmit information such as flight identification, altitude, and speed of the aircraft. Secondary radars are more precise than primary radars and are used in areas with heavy air traffic.

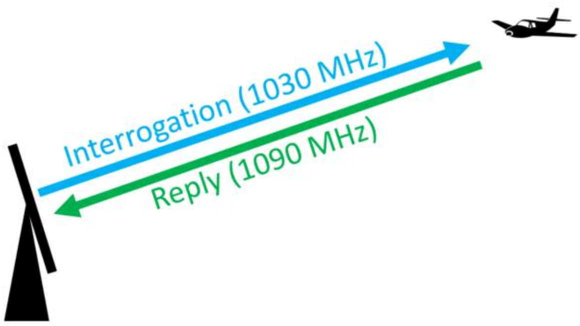

Fig 3.2 Secondary Surveillance Radar [16]

- AUTOMATIC DEPENDENT SURVEILLANCE – BROADCAST (ADS-B)

In addition, Eurocontrol uses a network of Automatic Dependent Surveillance-Broadcast (ADS-B) receiving stations [17], which allows aircraft to transmit their position, speed, and altitude information directly to air traffic controllers in real-time. This enables more precise and efficient surveillance of air traffic in European airspace.

According to EUROCONTROL, the Automatic Dependent Surveillance Broadcast system is currently implemented and being deployed in Europe, North America, and the Asia/Pacific regions, and is completely interoperable thanks to the EUROCAE and RTCA standards. Particularly, from July 7, 2020, and in the frame of the Single European Sky [1] the European Union requires all general aviation (GAT) aircraft flying under instrumental rules (IFR) and having a maximum take-off weight (MTOW) greater than 5,700 kg or a true airspeed greater than 250 knots, to comply with the ADS-B requirements.

Eurocontrol also uses the Multilateration (MLAT) position tracking system to complement its network of primary and secondary radars in areas where radar coverage is limited or non-existent, such as in mountainous regions or remote areas. It is also used at airports where obstacles may obstruct the line of sight of radars.

- MULTILATERATION (MLAT)

The MLAT system involves the use of four or more synchronized receivers that receive a signal from an aircraft and calculate the Time Difference of Arrival (TDOA). By comparing the TDOAs at which the signal is received by each ground receiver with a known position, it is possible to determine the 4-D location of the aircraft with an accuracy similar to that of ADS-B, which is around 10 to 20 meters. Fig 3.3 shows how the four synchronized receivers, sharing a reference time t_ref, detect the aircraft signal at four different TDOAs. Using the reference time, the four TDOAs, and the speed of sound (c=340 m/s), it is possible to calculate the distance between the target (aircraft) and each of the receivers. This system is an important tool for improving the accuracy and quality of flight tracking information in Europe.

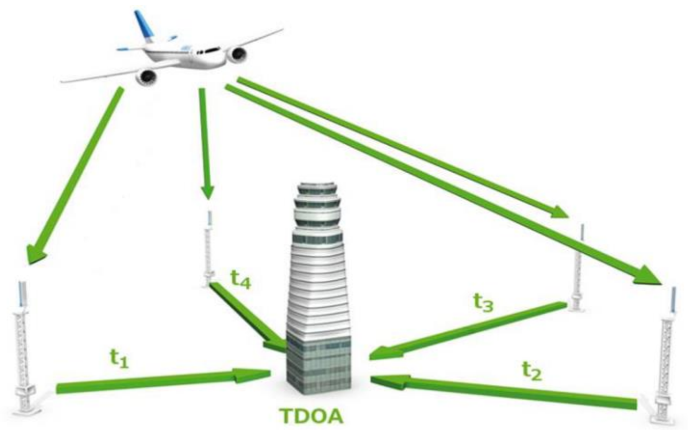

Fig 3.3 MLAT representation [17]

3.1.2. Data repository

The data obtained to study real cases has been obtained from a Eurocontrol repository called the Aviation Data Repository for Research [18]. There, you can find zip files containing monthly data from flights under Eurocontrol's responsibility, spanning from 2015 to 2020. The data includes information for four months of the year: March, June, September, and December. All the data is in .csv format, which allows for easy separation of information into different columns for filtering and selecting the required data.

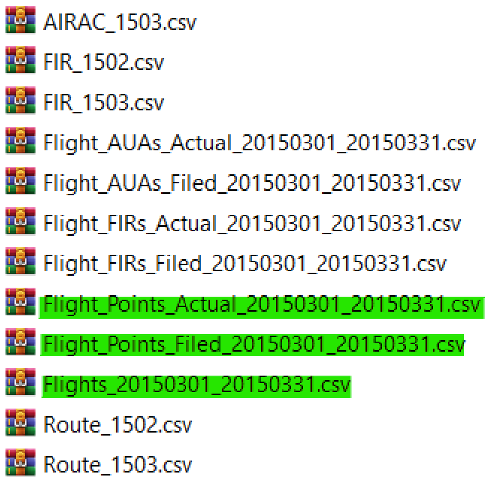

Fig 3.4 Zip files of each month

These zip files contain multiple CSV files, each corresponding to a specific month. However, for this project, only three of these CSV files were used for the demonstrations.

The first Excel file is named Flights_20XXXX_20XXXX, with each 'X' representing a different value for each month. This Excel file contains information about all the flights that took place during the respective month. The following details are provided for each flight:

ECTRL ID	ADEP	ADEP Latitude	ADEP Longitude	ADES	ADES Latitude	ADES Longitude	FILED OFF BLOCK TIME	FILED ARRIVAL TIME	ACTUAL OFF BLOCK TIME	ACTUAL ARRIVAL TIME	AC Type	AC Operator	AC Registration	ICAO Flight Type	STATFOR Market Segment	Requested FL	Actual Distance Flown (nm)
184408024	KORD	41.98	-87.905	EHAM	5.230.806	4.76417	01-03-2015 00:00:00	01/03/2015 7:34	01/03/2015 1:00	01/03/2015 8:19	B763	UAL	N661UA	S	Traditional Scheduled	330	3953

Fig 3.5 Flights information

The following information was extracted from the Flights_20XXXX_20XXXX Excel file:

- ECTRL ID
- ADEP (Departure Airport)
- ADES (Destination Airport)
- AC OPERATOR (Aircraft Operator)
- ACTUAL DISTANCE FLOWN (in nautical miles)

To classify the selected flight data for analysis, three filters were applied: one based on the ADEP column, another on the ADES column, and the last one on the AC operator column.

An extra column was added to obtain the actual flown distance in kilometres and considering the GCD. This means that 80 nautical miles have been subtracted, 40 for each side, from the value and then the value was converted to kilometres.

Additionally, there are two large files named Flight_Points_Actual and Flight_Points_Filed. These files contain sequences of coordinates for each flight, representing the route from the departure airport to the destination. The sampling of coordinates does not follow a constant pattern and varies for each flight. The difference between the two files is that Flight_Points_Actual displays the actual sequence of coordinates, while Flight_Points_Filed shows the filed sequence of coordinates.

The Flight_Points_Actual and Flight_Points_Filed files include the following information for each sequence number:

ECTRL ID	Sequence Number	Time Over	Flight Level	Latitude	Longitude
184408024	0	01/03/2015 1:00	0	41.98	-87.905
184408024	1	01/03/2015 1:25	0	41.98	-87.905
184408024	2	01/03/2015 1:47	330	42.06361	-84.32945
184408024	3	01/03/2015 2:05	330	42.03611	-80.75361
184408024	4	01/03/2015 2:23	330	41.89722	-77.17806
184408024	5	01/03/2015 2:41	330	41.64639	-73.60222
184408024	6	01/03/2015 3:00	330	41.28167	-70.02667
184408024	7	01/03/2015 3:15	330	41.11667	-67
184408024	8	01/03/2015 3:31	330	41.61445	-63.5
184408024	9	01/03/2015 3:46	330	42	-60
184408024	10	01/03/2015 4:02	330	42.77861	-56.66667
184408024	11	01/03/2015 4:17	330	43.44389	-53.33333
184408024	12	01/03/2015 4:31	330	44	-50
184408024	13	01/03/2015 4:46	350	44.78	-46.66667
184408024	14	01/03/2015 5:00	350	45.445	-43.33333
184408024	15	01/03/2015 5:14	350	46	-40
184408024	16	01/03/2015 5:27	350	46.78111	-36.66667
184408024	17	01/03/2015 5:41	350	47.44583	-33.33333
184408024	18	01/03/2015 5:54	350	48	-30
184408024	19	01/03/2015 6:07	350	48.78167	-26.66667
184408024	20	01/03/2015 6:20	350	49.44639	-23.33333
184408024	21	01/03/2015 6:33	350	50	-20
184408024	22	01/03/2015 6:42	350	50.02695	-17.5
184408024	23	01/03/2015 6:51	350	50	-15
184408024	24	01/03/2015 6:55	350	50	-14
184408024	25	01/03/2015 7:06	350	50.22278	-11
184408024	26	01/03/2015 7:17	350	50.36667	-8
184408024	27	01/03/2015 7:32	350	51.06945	-4.50389
184408024	28	01/03/2015 7:46	350	51.65	-1.00806
184408024	29	01/03/2015 8:00	230	52.11472	2.48806
184408024	30	01/03/2015 8:05	165	52.44806	3.42111
184408024	31	01/03/2015 8:08	97	52.52556	3.96722
184408024	32	01/03/2015 8:16	13	52.4025	4.71528
184408024	33	01/03/2015 8:19	0	52.30806	4.76417

Fig 3.6 Sampling of coordinates for the flight with ID: 184408024

From this file, the ECTRL ID, Latitude and Longitude for each sequence and flight had been used.

3.2. MATLAB functions

In order to analyse all this data, different Excel tools and MATLAB functions have been defined to work with.
The MATLAB functions employed for analysis vary depending on whether the focus is on the actual flight path or the filed flight path. Distinct sets of MATLAB functions are utilized for each scenario to handle the specific requirements and objectives related to analysing the respective flight paths.

3.2.1. Actual flight distance & KEA

In this case, a MAIN script and a KEA function were used to achieve the desired results by analysing the actual flown distance data from the Excel file "Flights_20XXXX_20XXXX". The KEA function was specifically designed to calculate the horizontal flight efficiency, as explained in Chapter 2.

The MAIN script begins by reading the data from the Excel file "Flights_20XXXX_20XXXX". It extracts the total number of flights and the actual flight distance for each flight, considering the GCD. The GCD is manually provided as an input parameter for the KEA calculation.

Using loops, the script calculates the KEA for each flight based on the provided actual flight distance and GCD. It then computes the mean KEA and mean actual flight distance considering the total number of flights.

Once all the calculations are completed, the script prints the following results:

- Total number of flights
- Mean flight distance for all the flights in the analysed month
- Mean KEA for all the flights in the analysed month

By displaying these results, the code provides valuable insights into the analysed flight data, allowing for a better understanding of the horizontal flight efficiency and other relevant statistics, which can be analysed easily with excel tools.

3.2.2. Filed flight distance & KEP

A new function was required to accurately calculate the flight distances since this information is not available in the 'Flights_20XXXX_20XXXX' file.

The 'obtainDistance' function takes two input arguments: the name of the Excel file containing the flight data and the flight ID for which you want to calculate the distance.

A pre-prepared list of flight IDs, comprising all flights departing from Barcelona and heading to Sevilla or Dublin, is used to sequentially search each ID in the 'Flight_Points_Filed' Excel file and compute their respective distances.
The distance calculation process involves the following steps:

1. Obtain the latitude and longitude coordinates of the desired flight and convert them from degrees to radians.
2. Starting from the first coordinate sequence, calculate the straight-line distance to the next coordinate sequence, using the Haversine equation explained in Chapter 2. Accumulate these distances until reaching the last coordinate sequence. Finally, subtract 80 nautical miles from the total result to analyse it in terms of Great Circle Distance.

Once the distances for the selected flights have been obtained, the KEP parameter is calculated using the same methodology as for the actual flight distance and KEA, considering the output from the 'obtainDistance' function.
Subsequently, the average distance and KEP values are computed, considering the total number of analysed flights.

Finally, the code returns the following information:

- Total number of flights.
- Mean flight distance for all the flights analysed during the given month.
- Mean KEP for all the flights analysed during the given month.

It is important to note that due to the large size of the 'Flight_Points_Filed' Excel file, it was not possible to read the entire dataset. Consequently, the number of sampled flights is significantly lower than in the previous section and so the accuracy of the results. Note that the limited number of samples may be a factor if the generated response lacks coherence or does not make much sense.

CHAPTER 4. ROUTE ANALYSIS

In this section, the data obtained from the MATLAB codes is shown per route. After showing the numbers in a table, these results are analysed in each section.

4.1 LEBL – LEZL route

The first route to be analysed is the Barcelona to Sevilla one. As shown in the Figure 4.1.1, this is the track that the pilots performed considering the actual flight distance.

Fig 4.1 Actual flight points of the flight with ID 238932501

It can be observed that the sampling frequency is not consistent, as there is a lack of references from the southeast part of Catalonia to Albacete. Every green point means a sample of coordinates.

After running the MATLAB codes, the results for this route are obtained and presented in the following table. The table consists of two main sections: one displaying the results for the actual route (highlighted in green), and the other displaying the results for the filed route (highlighted in blue). Each section includes the total number of flights, the mean flight distance, and the Key Performance Factor (KPF) computed on a monthly basis.

Table 4.1 Results for the LEBL - LEZL route

YEAR/MONTH	DEPARTURE	ARRIVAL	OPERATOR	ACTUAL NUMBER OF FLIGHTS	ACTUAL FLIGHT DISTANCE	MEAN KEA	FILED NUMBER OF FLIGHTS	FILED FLIGHT DISTANCE	MEAN KEP
201503	LEBL	LEZL	VLG	165	706,7	93,41	9	715	92,21
201506	LEBL	LEZL	VLG	161	706	93,41	10	733	89,48
201509	LEBL	LEZL	VLG	154	706	93,41	6	726	90,44
201512	LEBL	LEZL	VLG	124	704	93,83	9	830	74,87
201603	LEBL	LEZL	VLG	171	699	94,52	8	746	87,53
201606	LEBL	LEZL	VLG	198	699	94,52	12	746	87,45
201609	LEBL	LEZL	VLG	175	705	93,69	5	737	88,86
201612	LEBL	LEZL	VLG	115	716	92,01	10	937	58,7
201703	LEBL	LEZL	VLG	177	703	93,97	7	956,77	55,69
201706	LEBL	LEZL	VLG	187	693	95,36	11	748,57	81,66
201709	LEBL	LEZL	VLG	177	699	94,52	5	1087	35,93
201712	LEBL	LEZL	VLG	164	703	93,97	10	734	89,27
201803	LEBL	LEZL	VLG	184	697	94,8	10	799	79,48
201806	LEBL	LEZL	VLG	195	695	95,08	7	765	84,55
201809	LEBL	LEZL	VLG	194	721	91,18	2	700	94,39
201812	LEBL	LEZL	VLG	188	716	92,01	6	724	90,82
201903	LEBL	LEZL	VLG	194	727	90,34	8	873	68,28
201906	LEBL	LEZL	VLG	194	719	92,85	-	-	-
201909	LEBL	LEZL	VLG	191	712	92,57	-	-	-
201912	LEBL	LEZL	VLG	190	709	92,99	7	797	79,77
202003	LEBL	LEZL	VLG	114	699	94,52	7	698	94,59
202006	LEBL	LEZL	VLG	23	680	97,32	4	782	81,95
202009	LEBL	LEZL	VLG	68	712	92,57	6	741	88,23
202012	LEBL	LEZL	VLG	74	706	93,41	7	754	86,19

It should be noted that there is no available flight data for the months of June and September 2019 in the dataset.

The limited number of samples available for the field route analysis is a result of the inability to access the complete document of the Flight_Points_Filed. Only the initial flights of the document were accessible for analysis.

4.1.1. Actual flight distance

In this section, different graphics will help to analyse the data obtained for this route.

The first plot shows the number of flights per month:

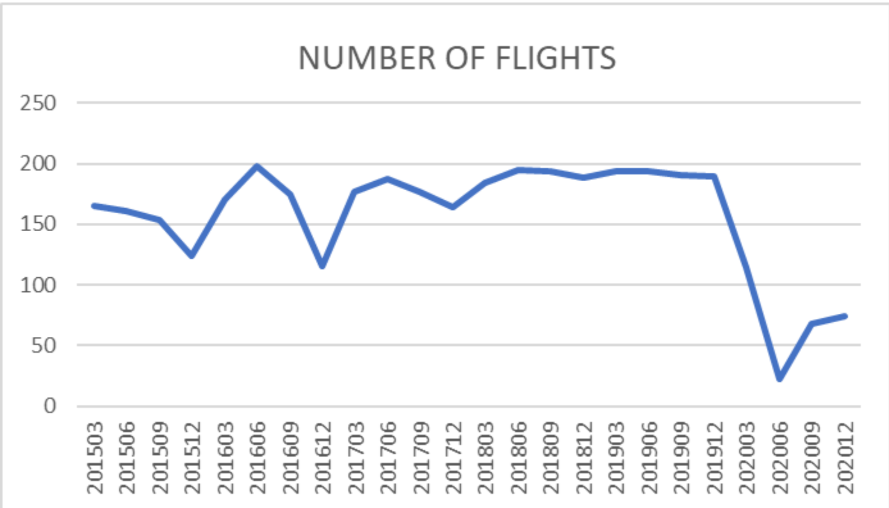

Fig 4.2 Number of flights per month

It is evident that the number of flights steadily increased until the onset of the COVID-19 pandemic, during which a significant number of flights were cancelled. In December 2015, 2016 and 2017 the flights number is low due to low season.

In the following plots, flight distances and KEA are shown per month:

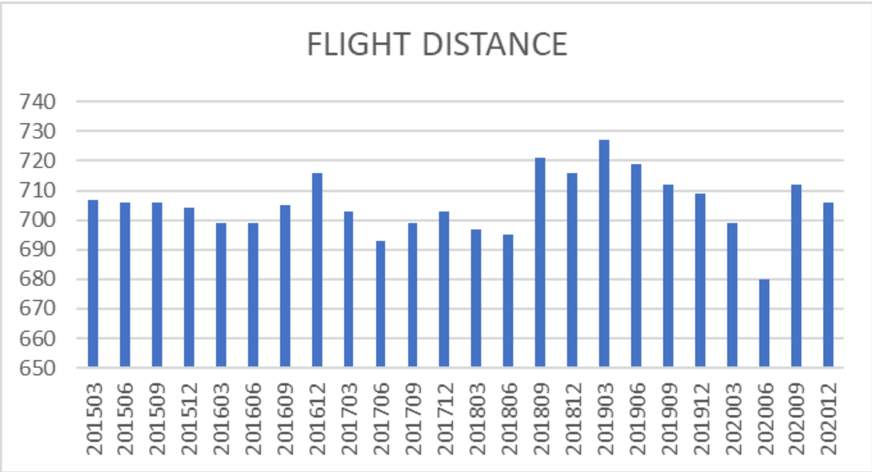

Fig 4.3 Flight distance per month

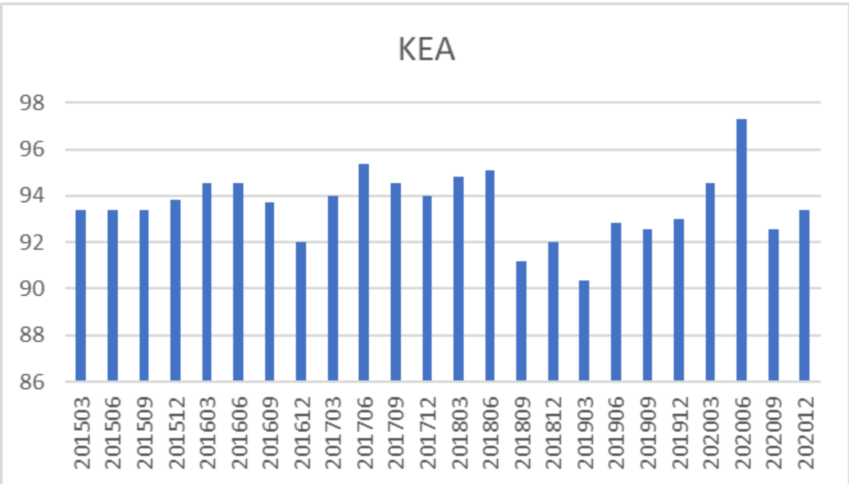

Fig 4.4 KEA per month

The KEA parameter had been gradually increasing over the years, because of the projects and implementations explained in CHAPTER 1, with a slight decline in 2018, possibly due to traffic congestion in the Spanish Airspace. However, when the pandemic struck and airspace experienced reduced traffic, the KEA value significantly increased.

Europapress published an article [19] in the beginning of 2019 that sheds light on the considerable decrease in KEA during 2018 and the beginning of 2019. According to the report, Spain witnessed a record-breaking total of 2 million flights crossing its airspace in 2018. The high volume of flights resulted in a reduced capacity, necessitating increased flight distances to ensure safety and separation for each individual flight. However, there was also a belief that this increasing trend of air traffic would not come to a halt. It is reflected in the mean KEA number for the rest of 2019.

When the COVID-19 pandemic struck, the capacity of airspace experienced a significant increase as the number of flights drastically decreased. This decrease in air traffic during 2020 can be attributed to the pandemic, and it helps to explain the subsequent increase in KEA during that year.

It is challenging to establish a direct correlation between these results and the Free Route Airspace concept in Spain, as flight distances in the region are not typically extensive and the project was not still implemented. The impact of Free Route Airspace implementation in Spain may be more significant in terms of enhancing flexibility, efficiency, and reducing congestion rather than directly influencing the KEA parameter based on flight distance.

4.1.2. Actual v.s. Filed flight distance & KEA v.s. KEP

In the following tables, KEA and KEP parameters are compared for this route.

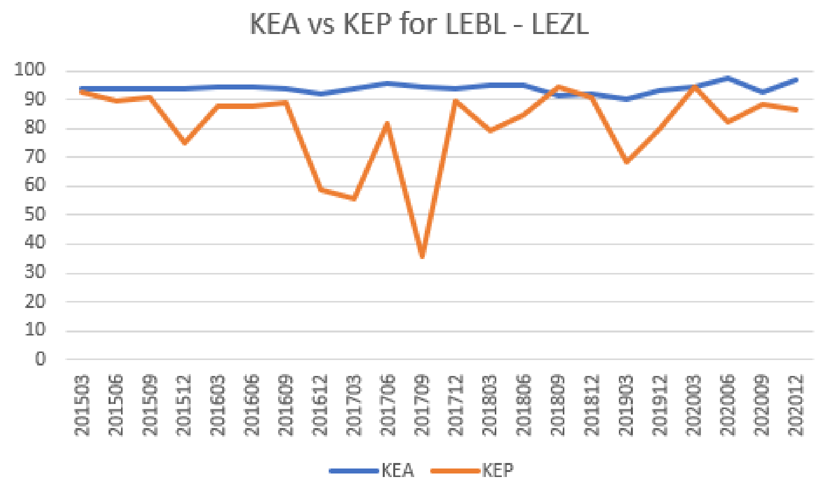

Fig 4.5 KEA and KEP comparison for the LEBL - LEZL route

In this route, from LEBL to LEZL, it is consistently evident that the KEA parameter is consistently higher than the KEP parameter. However, there is one exception in September 2018, where the trend is reversed. This anomaly could potentially be attributed to congestion in the Spanish Airspace, particularly during September when there is typically a high volume of flights due to seasonal factors or increased travel demand. The congestion during this period may have influenced the positioning estimates and resulted in the temporary reversal of the KEA and KEP relationship.

Another thing that can be observed is that the KEA and KEP have the tendency to be very similar in June and September and be different in March and December. This is clearly due to the travel demand in the summer months, where the flight numbers are multiplied by a high number worldwide. In March and December, where the traffic demand decreases, the capacity of all the airspace increases and there is more availability for the pilots and ATC to perform the best route in terms of efficiency.

It should be noted that the results for December of 2016 and the whole 2017 in the flight to LEZL may vary due to external factors, as explained earlier. Additionally, variations in the data could also occur due to potential errors in the coordinates recorded in the Excel file. Even a single error in any of the data points can have a significant impact and potentially introduce confusion or inaccuracies in the analysis. Therefore, it is important to consider the possibility of errors or inconsistencies in the coordinates when interpreting the results for the flight during the mentioned period.

The data for June and September of 2019 is unavailable or missing and has been removed from the records.

In this other table, the flight distance difference is shown. It is computed as the Actual Flight Distance subtracted to the Filed Flight Distance. Note that this distance is in terms of kilometres:

Table 4.2 Distance differences per month for LEBL – LEZL

MEAN KEP	MEAN DISTANCE DIFFERENCE	MEAN DIFFERENCE IN %
201503	8	1,12
201506	27	3,68
201509	20	2,75
201512	126	15,18
201603	47	6,30
201606	47	6,30
201609	32	4,34
201612	221	23,59
201703	254	26,52
201706	56	7,42
201709	388	35,69
201712	31	4,22
201803	102	12,77
201806	70	9,15
201809	-21	-3,00

201812	8	1,10
201903	146	16,72
201906	-	-
201909	-	-
201912	88	11,04
202003	-1	-0,14
202006	102	13,04
202009	29	3,91
202012	48	6,37

A total of 1827 km were saved from 2015 to 2020 considering all the flights of this period.

These results go completely related to the results of the KEA vs. KEP plot. As more as the KEA and KEP are very different, the higher the distance difference. The numbers with a "-" means that in those cases, the mean Filed Distance is higher than the mean Actual Distance.

The third column in the study represents the difference in distance between the actual flight distance and the filed distance, expressed as a percentage. However, the results obtained from this analysis may not be entirely conclusive due to several factors:

- Inaccuracy of filed distance: The filed distance, which serves as a reference for comparison, may not be highly precise. Consequently, this lack of accuracy can significantly impact the calculated results.

- Limited potential for distance reduction: As previously explained, the first route being analysed, Barcelona – Sevilla, is relatively short. Therefore, the opportunities for reducing the flight distance are inherently limited compared to longer routes.

Taking these factors into consideration, it is important to interpret the results with caution and recognize that the findings may not provide a comprehensive understanding of the impact of the Free Flow technique on distance reduction.

4.2. LEBL – EIDW

The other route to be analysed is the Barcelona to Dublín one. As shown in the Figure 4.2.1, this is the track that the pilots performed considering the actual flight distance.

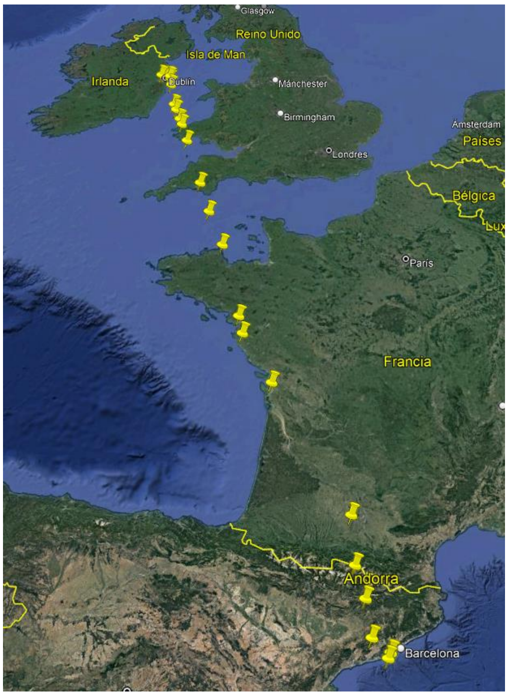

Fig 2.6 Actual flight points of the flight with ID 238931779

Now, after executing the MATLAB codes, the following results are obtained for this route. In the table there are two main parts, which are the results for the actual route (in green) and the results for the filed route (in blue). For each part, the total number of flights, the mean flight distance and the Key performance factor per month are computed.

Table 4.1 Results for the LEBL - EIDW route

YEAR/MONTH	DEPARTURE	ARRIVAL	OPERATOR	ACTUAL NUMBER OF FLIGHTS	ACTUAL FLIGHT DISTANCE	MEAN KEA	FILED NUMBER OF FLIGHTS	FILED FLIGHT DISTANCE	MEAN KEP
201503	LEBL	EIDW	RYR	64	1406	94,84	4	1546	84,35
201506	LEBL	EIDW	RYR	60	1414	94,22	3	1608	79,69
201509	LEBL	EIDW	RYR	60	1410	94,49	2	1600	80,37
201512	LEBL	EIDW	RYR	69	1406	94,84	3	1592	80,9
201603	LEBL	EIDW	RYR	77	1400	95,25	3	1592	80,91
201606	LEBL	EIDW	RYR	77	1411	94,42	2	1516	86,59
201609	LEBL	EIDW	RYR	78	1407	94,7	3	1633	77,86
201612	LEBL	EIDW	RYR	76	1414	94,22	4	1561	83,26
201703	LEBL	EIDW	RYR	80	1405	94,91	3	1535	85,17
201706	LEBL	EIDW	RYR	78	1407	94,7	3	1510	87,04
201709	LEBL	EIDW	RYR	74	1411	94,42	3	1475	89,66
201712	LEBL	EIDW	RYR	66	1389	96,08	3	1490	88,52
201803	LEBL	EIDW	RYR	67	1411	94,42	1	1538	84,9
201806	LEBL	EIDW	RYR	77	1420	93,73	3	1552	83,9
201809	LEBL	EIDW	RYR	77	1395	95,67	2	1588	81,2
201812	LEBL	EIDW	RYR	76	1394	95,74	3	1571	82,43
201903	LEBL	EIDW	RYR	81	1400	95,25	3	1565	82,91
201906	LEBL	EIDW	RYR	76	1410	94,56	-	-	-
201909	LEBL	EIDW	RYR	78	1402	95,12	-	-	-
201912	LEBL	EIDW	RYR	74	1383	96,57	3	1526	85,81
202003	LEBL	EIDW	RYR	50	1381	96,71	3	1575	82,21
202006	LEBL	EIDW	RYR	3	1369	97,61	0	0	0
202009	LEBL	EIDW	RYR	47	1382	96,64	3	1514	86,76
202012	LEBL	EIDW	RYR	16	1375	97,12	1	1406	94,81

4.2.1. Actual flight distance

This other flight is analysed to see what happens in a longer flight and with a crossing FRA which is being upgraded year by year.

This first plot shows the total amount of flights per month:

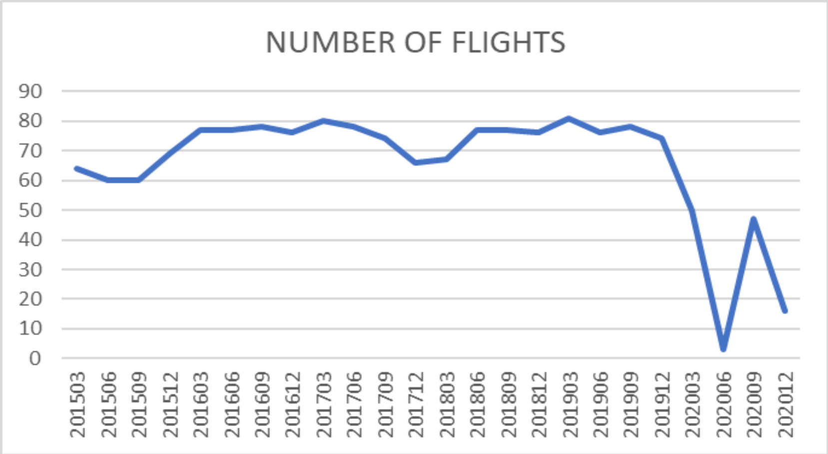

Fig 4.7 Number of flights per month

As previously explained, the number of flights remained constant until the global pandemic hit, causing a significant decrease in flight numbers worldwide.

In the following plots, flight distances and KEA are shown per month:

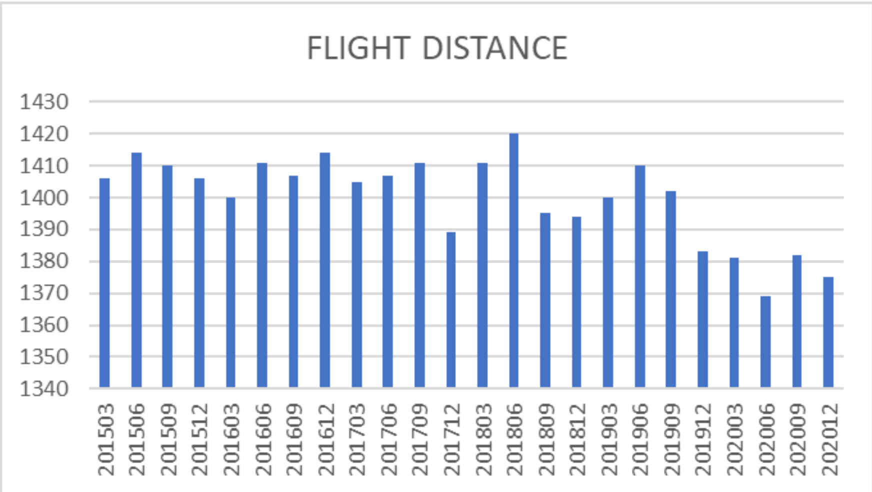

Fig 4.8 Flight distance per month

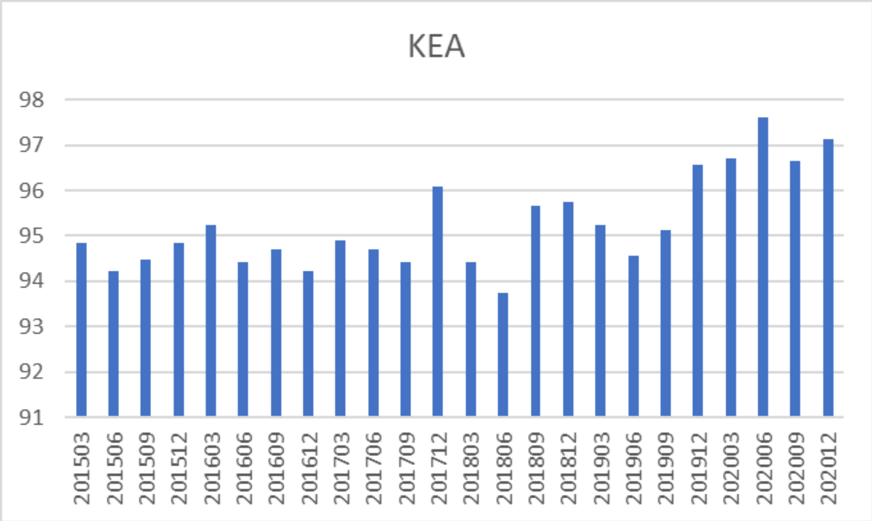

Fig 4.9 KEA per month

In this case, it is noted that the KEA parameter remained relatively stable over the years until June 2018, when it started to rise. This upward trend continued into 2020, coinciding with the onset of the COVID-19 pandemic. As the pandemic led to significant reductions in air traffic, airspace capacity was expanded to accommodate the minimal number of flights. The increase in the KEA parameter during this period can be attributed to the adjustments made to manage reduced air traffic demand and maximize the utilization of available airspace capacity. It can also be seen that while the air traffic was being recovered from the low flight numbers of the pandemic, the KEA did not decrease, it was maintained at the top levels, which represents a key factor for the following years for the air traffic management.

In difference with the Spanish case, the ongoing improvement of Free Route Airspace (FRA) in Europe contributes to the effective management of increased air traffic and the stability of the KEA parameter. FRA allows for more direct flight paths, independent of traditional air traffic control boundaries, optimizing airspace capacity and reducing congestion.

As FRA continues to expand and improve, it enhances the air traffic management system's ability to handle growing traffic volumes while maintaining efficiency. FRA plays a significant role in supporting the overall performance of air traffic management.

To explain this section a little better, I had a call with my friend Marc, who is a pilot for RYR. I asked him if he had ever flown the route LEBL – EIDW, and fortunately, he said yes. He was able to provide me with the flight routing:

LEBL/24L NATPI DCT EVNAM DCT AGN DCT SECHE DCT UVELI DCT CNA DCT MANAK UY110 TIRAV UT183 BAGAD DCT DOLUR DCT UPCAB DCT 0VFOX DCT EVRIN BUNED BUNED2R EIDW/10R

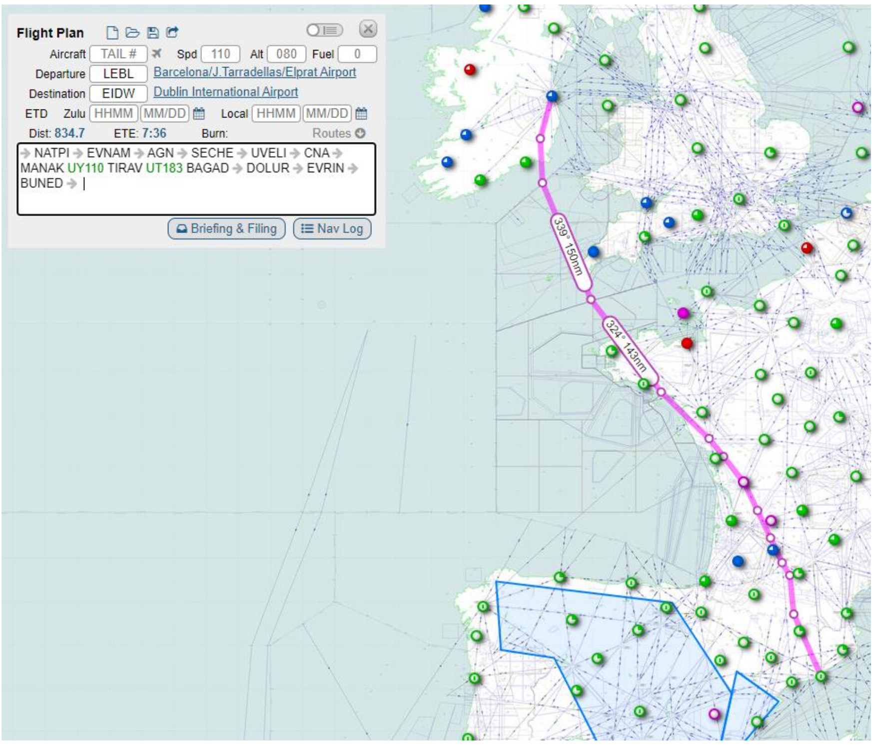

Fig 4.10 Routing in SkyVector for the Planned Route [20]

After viewing the planned route on SkyVector, he told me that the last time he flew the route, he received authorization from the ATC while flying, to go directly from the NATPI point to DOLUR. Therefore, the actual route was as follows:

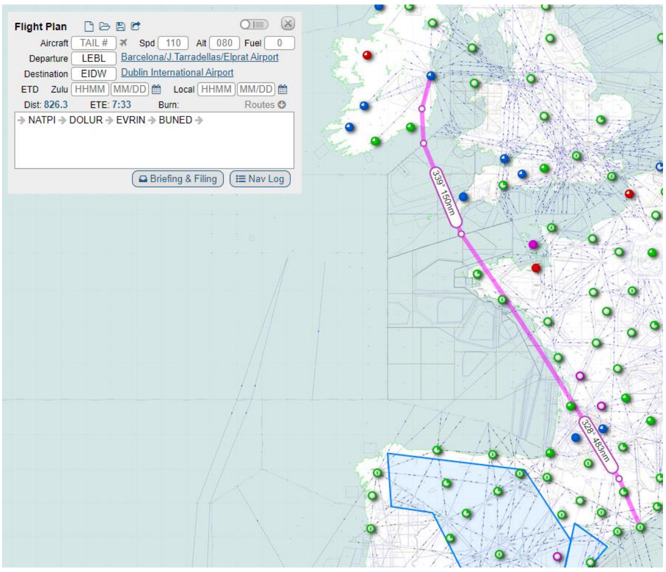

Fig 4.11 Routing in SkyVector for the Actual Route [20]

Zooming in on the cropped area, we see the following:

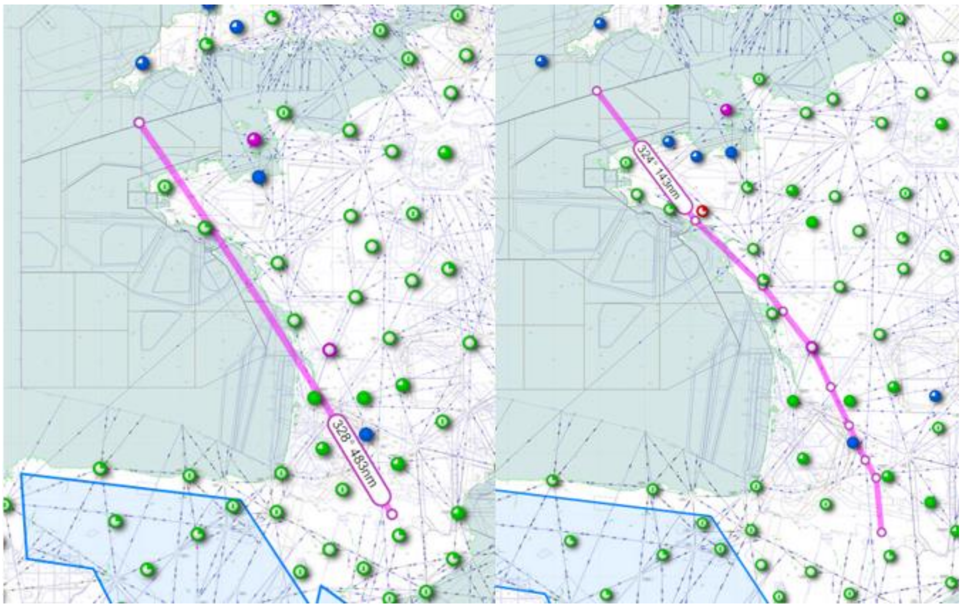

Fig 4.12 Actual vs Planned NATPI to DOLUR [20]

It is clearly noticeable that the distance is reduced, thereby increasing the horizontal efficiency of the flight. Specifically, in this track between NATPI and DOLUR, there is a difference of 491.4 - 483 = **8.4** nautical miles, which is equivalent to **155 km**. In other terms, there is a 1,7% reduction of the flight distance in this section of the flight.

If the flight had to go through UK airspace, he mentioned that often ATCs authorize you to go directly from the entry point of the FIR to the exit point, without the need to go point-to-point, which develops the concept of Free Flow.

This case provides a practical illustration of the utilization of Free Flow operations in aviation, reinforcing the conclusions drawn in this project section, specifically concerning the NATPI to DOLUR segment of the route.

By obtaining authorization to fly directly from the NATPI waypoint to DOLUR, the pilot effectively bypasses the need for additional intermediate waypoints, resulting in a more efficient and streamlined flight path. This direct routing significantly reduces the distance travelled, saving both time and fuel consumption.

Therefore, this practical demonstration serves as compelling evidence that Free Flow operations are actively employed, further reinforcing the conclusions made in this project regarding the advantages of streamlined air traffic flow and the benefits it brings, particularly for this specific route between NATPI and DOLUR.

4.2.2. Actual v.s. Filed flight distance & KEA v.s. KEP

In this plot it is observed the same as the other route: the KEA is always higher than the KEP.

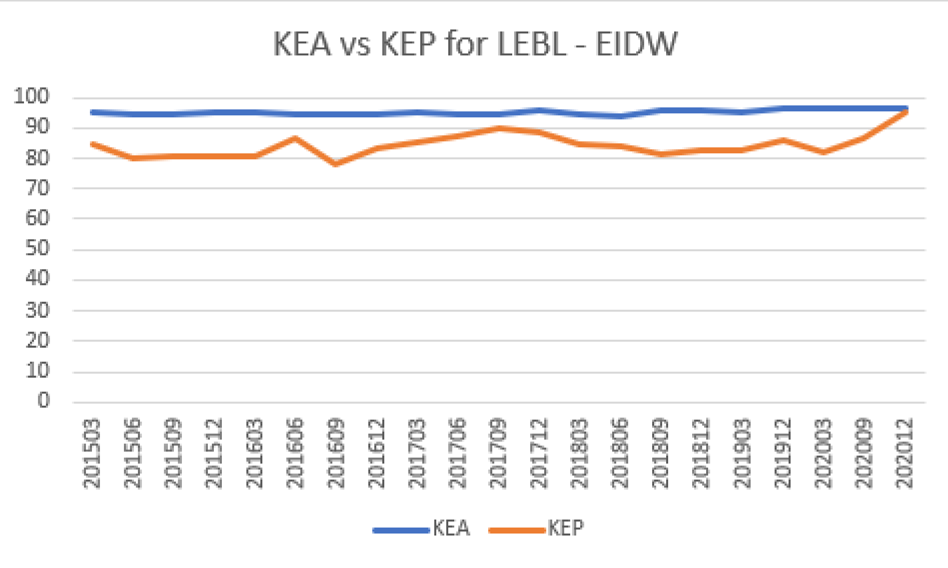

Fig 4.13 KEA and KEP comparison for the LEBL - EIDW route

Comparing both lines, it becomes evident that the flight to LEZL, which covers a shorter distance, allows for less time to deviate significantly from the GCD. Consequently, the KEA and KEP values tend to be very similar.

On the other hand, the flight to EIDW, covering a considerable distance, it is easier to have a lower KEP as the flight has a wider range of theoretical points to follow along the filed route and much more constraints in the route such as forbidden zones. However, it provides more opportunities to explore alternative flight paths and optimize efficiency as flying through a FRA, increasing the potential for KEA improvement. This is what airlines do. They observe the filed route and tell the pilots to try to avoid some segments to make the route more efficient.

This observation aligns with the understanding that shorter flights with limited time for deviations from the GCD would result in KEA and KEP values that are closely aligned. Conversely, longer flights offer more flexibility in selecting efficient flight paths, leading to a lower KEP value and potential improvements in KEA.

The data for June and September of 2019 and June of 2020 is unavailable or missing and has been removed from the records.

Here the table with the distance difference from this flight:

Table 4.4 Distance differences per month for LEBL – EIDW

YEAR/MONTH	DISTANCE DIFFERENCE	DIFFERENCE IN %
201503	140	9,06
201506	194	12,06
201509	190	11,88
201512	186	11,68
201603	192	12,06
201606	105	6,93
201609	226	13,84
201612	147	9,42
201703	130	8,47
201706	103	6,82
201709	64	4,34
201712	101	6,78
201803	127	8,26
201806	132	8,51
201809	193	12,15
201812	177	11,27
201903	165	10,54
201906	-	-
201909	-	-
201912	143	9,37
202003	194	12,32
202006	-	-
202009	132	8,72
202012	31	2,20

A total of 3072 kilometres were saved from 2015 to 2020 considering all the flights of this period.

It is now evident that there is a correlation between longer flight distances and greater disparities between the filed and actual distances. As mentioned earlier, these findings are closely associated with the KEA vs. KEP plot.

In this case, the third column serves to provide a clearer understanding of the distance savings achieved. Since the Barcelona – Dublin route is longer compared to the Barcelona – Sevilla route, there is more room and time available to potentially reduce the actual distance flown. The data indicates a consistent average reduction of approximately 10% in all months, which, considering the longer route, represents a significant achievement.

4.3. Fuel saved and CO2 emissions

In this section, the objective is to provide an estimate of the fuel consumption saved and the CO_2 for the LEBL – EIDW route, operated by Ryanair. As shown in the Eurocontrol repository data, all these flights were performed with a Boeing 737-800.

To accomplish this, the following reference will be considered:

“Without wind, the Boeing 737-800 consumes about 358 litres per 100 km, that is, approximately 1 in 0.3. Consumption depends on the speed at which you fly. Normally consumption is indicated at cruising speed. For this aircraft, the average is about 839 km/h with a consumption of about 3,000 litres per hour.” [21]

By considering these references, an approximation of the fuel consumption saved for the LEBL – EIDW route can be derived. Considering only the cruise phase simplifies the calculation of fuel consumption, as it eliminates the need to account for taxiing, climbing, and approaching operations, which are more complex factors. By focusing solely on the cruise phase, the analysis can concentrate on the fuel consumption during sustained level flight.

According to the Eurocontrol data, since there is no specific speed reference available, we will assume an average speed of 839 km/h for the flight and the airplane. Additionally, the estimated fuel consumption for this speed is approximately 3,000 litres per hour, or alternatively, 358 litres per 100 km.

Table 4.5 Fuel savings in litres

YEAR/MONTH	ACTUAL FUEL CONSUMPTION	FILED FUEL CONSUMPTION	FUEL SAVED	FUEL SAVED IN %
201503	5033	5535	501	9,06
201506	5062	5757	695	12,06
201509	5048	5728	680	11,88
201512	5033	5699	666	11,68
201603	5012	5699	687	12,06
201606	5051	5427	376	6,93
201609	5037	5846	809	13,84
201612	5062	5588	526	9,42
201703	5030	5495	465	8,47
201706	5037	5406	369	6,82
201709	5051	5281	229	4,34
201712	4973	5334	362	6,78
201803	5051	5506	455	8,26
201806	5084	5556	473	8,51
201809	4994	5685	691	12,15
201812	4991	5624	634	11,27
201903	5012	5603	591	10,54
201906	5048	-	-	-
201909	5019	-	-	-
201912	4951	5463	512	9,37
202003	4944	5639	695	12,32
202006	4901	-	-	-
202009	4948	5420	473	8,72

202012	4923	5033	111	2,20

The second and the third column of Table 4.5 have been computed as follows:

$$SAVED\ FUEL\ (L) = DISTANCE\ DIFFERENCE\ (km) * 3{,}58\ \left(\frac{l}{km}\right) \qquad \textbf{(4.1)}$$

Table 2.6 Summary of the fuel saved per year in litres

2015	2016	2017	2018	2019	2020
2542	2399	1425	2252	1103	1278

As the difference in percentage has been calculated based on the distance difference, it can be observed that the difference in percentage is equal to the distance difference. In other words, if the distance difference between the actual flight distance and the filed distance is, for example, 10%, then the difference in percentage of fuel consumed would also be 10%. This implies that the percentage difference in distance aligns with the percentage difference in fuel consumption.

Over the period from 2015 to 2020, considering March, June, September and December, a total of **10.998 litres** of fuel were saved for the route LEBL – EIDW. This significant reduction in fuel consumption represents the cumulative amount of fuel that was conserved during that time frame.

This value is not much precise, as per June and September of 2019 and June of 2020 we have no values to add to the computation.

It is important to note that the total amount of fuel consumed would be significantly higher if we considered all phases of the flight. Taxiing, climbing, and approaching have a much higher fuel consumption proportionally compared to the cruise phase, as the engines are continuously operating.

So, in relation to the previous paragraph, it is evident that the route from LEBL to LEZL would have greater fuel consumption in proportion to the route from LEBL to EIDW. This is because the former has a shorter cruising time due to the shorter distance of the route.

Another method that can be utilized to calculate fuel consumption is Eurocontrol's Integrated Aircraft Noise and Emissions Modelling Platform (IMPACT) [22]. This platform incorporates various models designed to evaluate requirements based on diverse input parameters, including trajectories, engine thrust, mean velocity, and more. Notably, IMPACT integrates certain models from other platforms, such as Eurocontrol's Advanced Emissions Model (AEM) [23], which estimates fuel burned mass and corresponding gaseous emissions.

The outcomes are derived by utilizing diverse sources of information, such as the ICAO Aircraft Engine Emissions Databank [24] and Eurocontrol's Base of Aircraft Data (BADA). However, due to licensing issues, access to AEM was not available, and thus it was not considered as an option for computing fuel consumption.

When considering CO2 emissions, we will use the following statement to calculate the emissions saved due to the difference in distance:

Ryanair had a carbon intensity of 76g CO_2 pax/km in FY22 and 83g CO_2 pax/km in FY21. “We remain committed to reducing emission intensity by 10% from prepandemic levels (66g CO_2 pax/km) to 60g CO_2 pax/km by 2030.” [25]

In the following study we will consider the following parameters:

- Prepandemic emission levels: 66g CO_2 pax/km
- Load factor of 97% [26]
- Passengers for the B737-800: 189
- Number of kilometres of distance difference calculated before

Table 4.7 CO2 emissions related to the distance difference and the load factor

YEAR/MONTH	ACTUAL CO2 EMISSIONS	FILED CO2 EMISSIONS	EMISSIONS SAVED	EMISSIONS SAVED IN %
201503	16982	18673	1691	9,06
201506	17078	19421	2343	12,06
201509	17030	19325	2295	11,88
201512	16982	19228	2247	11,68
201603	16909	19228	2319	12,06
201606	17042	18310	1268	6,93
201609	16994	19723	2730	13,84
201612	17078	18854	1775	9,42
201703	16970	18540	1570	8,47
201706	16994	18238	1244	6,82
201709	17042	17815	773	4,34
201712	16776	17996	1220	6,78
201803	17042	18576	1534	8,26
201806	17151	18745	1594	8,51
201809	16849	19180	2331	12,15
201812	16837	18975	2138	11,27
201903	16909	18902	1993	10,54
201906	17030	-	-	-
201909	16933	-	-	-
201912	16704	18431	1727	9,37
202003	16680	19023	2343	12,32
202006	16535	-	-	-
202009	16692	18286	1594	8,72
202012	16607	16982	374	2,20

The second and the third column of the following table have been computed as follows:

$$CO_2\ EMISSIONS\ (KG) = \frac{66 * distance\ difference\ (km) * load\ factor * pax}{1000} \quad \textbf{(4.2)}$$

A total of **37.103 kilograms of CO2** were saved when comparing the actual route to the filed route. However, it is important to note that this number is not entirely objective, as it would be much higher if all phases of the flight were considered. In terms of percentage, it would be a reduction of around 10% per month.

Referring back to the Eurocontrol data, specifically the AEM report, it states the following:

"

The emissions for the H2O and CO2 pollutants are a direct result of the oxidation process of the carbon and hydrogen contained in the fuel with the oxygen contained in the atmosphere. The SOx emissions depend directly on the sulphur content of the fuel used. All three are directly proportional to the amount of fuel burnt."

"

Stated differently, the calculation of these three greenhouse gas emissions can be derived by determining the amount of fuel burned.

Another significant emission of concern is that of nitrogen oxides (NOx), which plays a role in the formation of contrails and contributes significantly to overall atmospheric warming [27]. While the relationship between NOx emissions and fuel consumption is not strictly proportional, a study conducted by the European Environment Agency [28] provides average values that allow for the computation of NOx emissions based solely on the kilograms of fuel consumed. Table 4.8 presents a summary of the kilograms of these gaseous emissions per kilogram of fuel.

Table 4.8 Non-engine-specific emissions (kg) per kg of fuel

CO2 [kg]/ fuel [kg]	H2O [kg]/ fuel [kg]	SOx [kg]/ fuel [kg]	NOx [kg]/ fuel [kg]
3.16	1.237	0.00084	0.004

Given the density of Jet-A1 fuel, which is 1.2438 litres per kilogram [29], this information provides a basis for further calculations and analysis.

The total kilograms of fuel saved are computed as follows:

$$\frac{1\,kg}{1.2438\,l} * TOTAL\ LITRES\ SAVED = \frac{1\,kg}{1.2438\,l} * 10.998 = 8.842\,kg \qquad \textbf{(4.3)}$$

A total of **8.842 kg** of fuel were saved in the route LEBL to EIDW just considering the cruise phase of the flight between 2015 and 2020. Now we can compute the total non-engine-specific emissions saved considering the distance difference:

$$H2O = 1{,}237 * 8.842 = 10.938\ kg\ of\ H2O$$

$$SOx = 0{,}00084 * 8.842 = 7{,}42\ kg\ of\ SOx$$

$$NOx = 0{,}004 * 8.842 = 35{,}36\ kg\ of\ NOx$$

It is evident that if we were to compute the difference in percentage based on the distance difference, the results would align with the difference in distance and with the difference of fuel consumption. Since the fuel consumption is directly related to the distance covered, the percentage difference in those emissions would correspond to the percentage difference in distance. Therefore, the calculations using the percentage difference would yield the same results as those obtained from the distance difference analysis.

These values may appear to be low when considering only one route and four months of the year. However, when considering all flights under Eurocontrol's control, these values become significantly high. This necessitates the search for solutions or alternatives to reduce the environmental impact of aviation.

4.4 Money saved considering the fuel saved

To calculate the savings per passenger per flight for Ryanair on the LEBL – EIDW route, we can use the provided data:

- Mean fuel cost: 1.61 euros per kilogram [30]
- Fuel saved in kg per month
- Load Factor: 97%
- Number of seats on the B737-800: 189

With this data, the following table has been reproduced:

Table 4.9 Money saved per pax per flight

MONTH	FUEL SAVED	FUEL SAVED PER SEAT	MONEY SAVED PER SEAT	MONEY SAVED PER PAX
201503	501	2,65	4,27	4,40
201506	695	3,67	5,92	6,10
201509	680	3,60	5,79	5,97
201512	666	3,52	5,67	5,85
201603	687	3,64	5,86	6,04
201606	376	1,99	3,20	3,30
201609	809	4,28	6,89	7,11
201612	526	2,78	4,48	4,62
201703	465	2,46	3,96	4,09
201706	369	1,95	3,14	3,24
201709	229	1,21	1,95	2,01
201712	362	1,91	3,08	3,18
201803	455	2,41	3,87	3,99
201806	473	2,50	4,03	4,15
201809	691	3,66	5,89	6,07
201812	634	3,35	5,40	5,56
201903	591	3,13	5,03	5,19
201906	-	-	-	-
201909	-	-	-	-
201912	512	2,71	4,36	4,50
202003	695	3,67	5,92	6,10
202006	-	-	-	-
202009	473	2,50	4,03	4,15
202012	111	0,59	0,95	0,97

The process to calculate the money saved per pax is the following:

1. First, we need to calculate the fuel saved per seat. To do so, the number of fuel saved is divided by the number of seats in the third column.

2. Then, to transform this number in euros, the number of fuel saved per seat is multiplied by the price of the kg of fuel [30], and the results are shown in the fourth column.

3. Considering that not all the flight were full booked, the load factor has been taken into account in the fifth column. To do so, the money saved per pax has been divided by the load factor.

Therefore, based on the given parameters and data for the LEBL – EIDW route, Ryanair would save approximately a mean of 4,60 €/pax per flight.

The amount of money saved per passenger can have a significant impact on an airline's financial performance. For example:

- Cost Reduction: The savings per passenger directly contribute to reducing the airline's operating costs. Fuel is one of the major expenses for airlines, so any reduction in fuel consumption and associated costs can lead to improved profitability.

- Increased Profit Margins: By saving money on fuel, the airline's profit margins can increase. These savings can positively impact the airline's bottom line, especially if the savings are consistent across multiple flights and routes.

- Competitive Advantage: Lower operating costs can give the airline a competitive advantage over other carriers. With cost savings, the airline may be able to offer more competitive ticket prices or invest in other areas, such as improving services or expanding routes.

- Environmental Sustainability: Fuel savings also result in a reduction in carbon emissions and environmental impact. This can enhance the airline's sustainability profile and appeal to environmentally conscious travelers, potentially attracting more customers and positively influencing the airline's reputation.

- Financial Stability: Cost savings per passenger contribute to the overall financial stability of the airline. By reducing costs, the airline can better navigate economic downturns, fuel price fluctuations, or other unforeseen challenges in the industry.

CHAPTER 5. CONCLUSIONS

The focus of this project was to investigate the implementation of Free Route Airspace (FRA) throughout Europe and analyse the flights operated by Vueling from Barcelona to Sevilla and Ryanair from Barcelona to Dublin between 2015 and 2020. The analysis considered various factors such as flight distance, efficiency, fuel consumption, and emissions. The hypothesis was that the actual flight distance should not exceed the filed flight distance. MATLAB codes, Excel tables, and functions were designed to demonstrate this hypothesis.

The primary objective was to calculate the difference between the actual flight distance and the filed flight distance, as it served as the basis for computing other factors. After performing the computations, clear and insightful values were obtained, highlighting the positive outcomes resulting from the implementation of FRA.

The case study revealed the following main results:

- The route from LEBL to LEZL saved 1,827 km, 9,46% per route
- The route from LEBL to EIDW saved 3,072 km, 9,37% per route

Considering the reduction of 9,37% of the flight distance, the route from LEBL to EIDW, also resulted in:

- 10,998 litres of fuel were saved.
- Saving of 37,103 kg of CO_2.
- Saving of 10,938 kg of H_2O.
- A reduction of 7.42 kg of SO_x was observed.
- Decrease of 35.36 kg of NO_x emissions.
- Money savings of 4,60 € per passenger per flight.

These results clearly demonstrate the benefits of implementing FRA. By reducing the distance travelled during flights, both emissions and fuel consumption are minimized. These reductions not only contribute to environmental sustainability but also lead to cost savings for airlines over the analysed period.

It is important to note that while the results obtained from this study are informative, their accuracy is somewhat limited. Despite utilizing the available data to the best of our abilities, more advanced techniques would be necessary to achieve more precise calculations.

In conclusion, I would like to revisit this project once the implementation of FRA in Europe has been completed by 2030. By then, it is expected that the results will continue to improve year after year, culminating in significant benefits by 2030. This would provide a more comprehensive understanding of the positive impact of FRA on flight efficiency, fuel consumption, and emissions reduction.

BIBLIOGRAPHY

[1] *Single European Sky*. (n.d.). Retrieved June 22, 2023, from https://www.enaire.es/about_enaire/international_presence/single_european_sky

[2] Guo, F., Chen, J., Zhang -, W., Li, X., Qing Chen, X., Xuan Wei -, D., Majka, A., & Pasich, A. (n.d.). *You may also like The Researches on Planning of Airline Network under Flexible Airspace Usage Design of general aviation airspace planning and management system based on Google Earth Jing Mou-Comprehensive Evaluation of Airspace and Ground Operation Simulation in Large-Scale Airport Cross-border Free Route Airspace concept and its impact on flight efficiency improvement*. https://doi.org/10.1088/1757-899X/1226/1/012022

[3] de Villardi, A. (2021). *Models for Air Traffic Management*.

[4] *Free Route Airspace (FRA) | SKYbrary Aviation Safety*. (n.d.). Retrieved July 6, 2023, from https://www.skybrary.aero/articles/free-route-airspace-fra

[5] *FREE FLIGHT, ¿LA NAVEGACIÓN AÉREA QUE VIENE?* (n.d.). Retrieved July 6, 2023, from https://www.hispaviacion.es/free-flight-la-navegacion-aerea-que-viene-2/

[6] *Free route airspace at Maastricht UAC (FRA@MUAC) | EUROCONTROL*. (n.d.). Retrieved July 6, 2023, from https://www.eurocontrol.int/service/free-route-airspace-maastricht-uac

[7] *Free route airspace (FRA) implementation projection charts | EUROCONTROL*. (n.d.). Retrieved July 6, 2023, from https://www.eurocontrol.int/publication/free-route-airspace-fra-implementation-projection-charts

[8] *HISPAFRA: freedom in the air | ITRANSPORTE*. (n.d.). Retrieved July 6, 2023, from https://www.revistaitransporte.com/hispafra-freedom-in-the-air/

[9] *¿What is Free-Route airspace?* (n.d.). Retrieved July 6, 2023, from https://www.enaire.es/services/atm/free_route/what_is_freeroute_airspace

[10] Gascon De Alaminos, A. (n.d.). *Título: Flight distance modelling to evaluate flight efficiency and environmental impact*.

[11] *Great-circle distance - Wikipedia*. (n.d.). Retrieved July 6, 2023, from https://en.wikipedia.org/wiki/Great-circle_distance

[12] *Haversine formula - Calculate geographic distance on earth*. (n.d.). Retrieved July 6, 2023, from https://www.igismap.com/haversine-formula-calculate-geographic-distance-earth/

[13] *Map projections and distortion*. (n.d.). Retrieved July 6, 2023, from http://www.geography.hunter.cuny.edu/~jochen/gtech361/lectures/lecture04/concepts/Map%20coordinate%20systems/Map%20projections%20and%20distortion.htm

[14] *Earth radius - Wikipedia*. (n.d.). Retrieved July 6, 2023, from https://en.wikipedia.org/wiki/Earth_radius

[15] *Primary Surveillance Radar (PSR) | SKYbrary Aviation Safety*. (n.d.). Retrieved July 6, 2023, from https://skybrary.aero/articles/primary-surveillance-radar-psr

[16] *Secondary Surveillance Radar (SSR) | SKYbrary Aviation Safety*. (n.d.). Retrieved July 6, 2023, from https://skybrary.aero/articles/secondary-surveillance-radar-ssr

[17] *Automatic dependent surveillance – broadcast (ADS-B) | EUROCONTROL*. (n.d.). Retrieved July 6, 2023, from https://www.eurocontrol.int/service/automatic-dependent-surveillance-broadcast

[18] *Archive data for R&D*. (n.d.). Retrieved July 6, 2023, from https://ext.eurocontrol.int/prisme_data_provision_hmi/

[19] *España supera en 2018 la barrera de los dos millones de vuelos en su espacio aéreo*. (n.d.). Retrieved July 6, 2023, from https://www.europapress.es/turismo/transportes/aeropuertos/noticia-espana-supera-2018-barrera-dos-millones-vuelos-espacio-aereo-20190114184407.html

[20] *SkyVector: Flight Planning / Aeronautical Charts*. (n.d.). Retrieved July 6, 2023, from https://skyvector.com/

[21] *Boeing 737-800*. (n.d.). Retrieved July 6, 2023, from https://www.flyouts.com/es/vliegtuig/boeing-737-800

[22] *Integrated aircraft noise and emissions modelling platform (IMPACT) | EUROCONTROL*. (n.d.). Retrieved July 6, 2023, from https://www.eurocontrol.int/platform/integrated-aircraft-noise-and-emissions-modelling-platform

[23] *Advanced emission model (AEM) | EUROCONTROL*. (n.d.). Retrieved July 6, 2023, from https://www.eurocontrol.int/model/advanced-emission-model

[24] *ICAO Aircraft Engine Emissions Databank | EASA*. (n.d.). Retrieved July 6, 2023, from https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

[25] *Ryanair 2022 Sustainability Report Interactive* Retrieved July 6, 2023, from https://corporate.ryanair.com/wp-content/uploads/2022/07/Ryanair-2022-Sustainability-Report-Interactive.pdf

[26] *Ryanair | Traffic*. (n.d.). Retrieved July 6, 2023, from https://investor.ryanair.com/traffic/#twentyone

[27] *Issue Brief | The Growth in Greenhouse Gas Emissions from Commercial Aviation (2019, revised 2022) | White Papers | EESI*. (n.d.). Retrieved July 6, 2023, from https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

[28] *EMEP/EEA air pollutant emission inventory guidebook — European Environment Agency*. (n.d.). Retrieved July 6, 2023, from https://www.eea.europa.eu/themes/air/air-pollution-sources-1/emep-eea-air-pollutant-emission-inventory-guidebook

[29] *Jet fuel - Wikipedia*. (n.d.). Retrieved July 6, 2023, from https://en.wikipedia.org/wiki/Jet_fuel

[30] *Gasolina de aviación - Precio Mensual (Euro por Galón) - Precios de Materias Primas*. (n.d.). Retrieved July 6, 2023, from https://www.indexmundi.com/es/precios-de-mercado/?mercancia=gasolina-de-aviacion&meses=60&moneda=eur

ANNEX 1

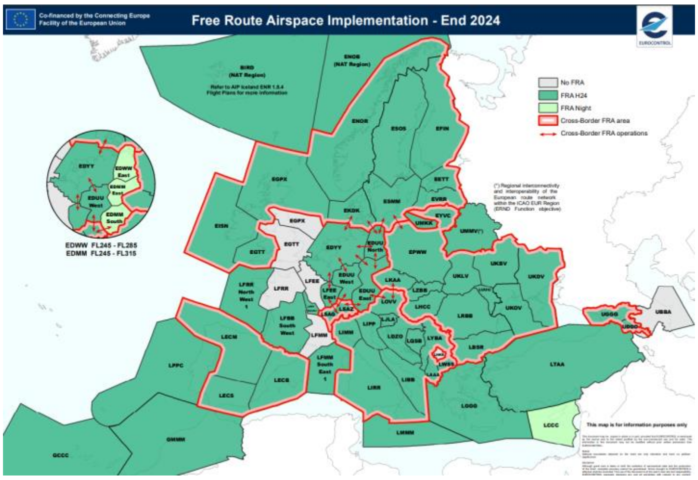

Fig 1.1 Free Route Airspace Implementation - End 2024

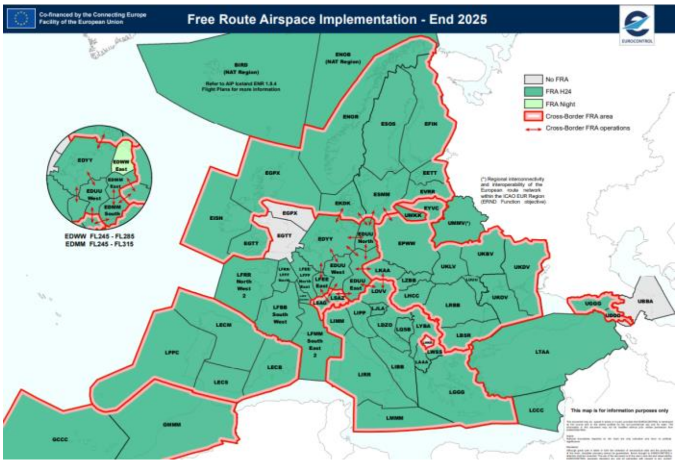

Fig 1.2 Free Route Airspace Implementation - End 2025

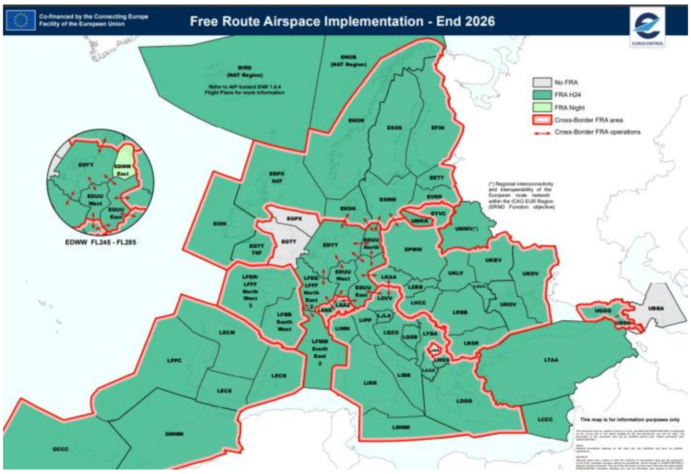

Fig 1.3 Free Route Airspace Implementation - End 2026

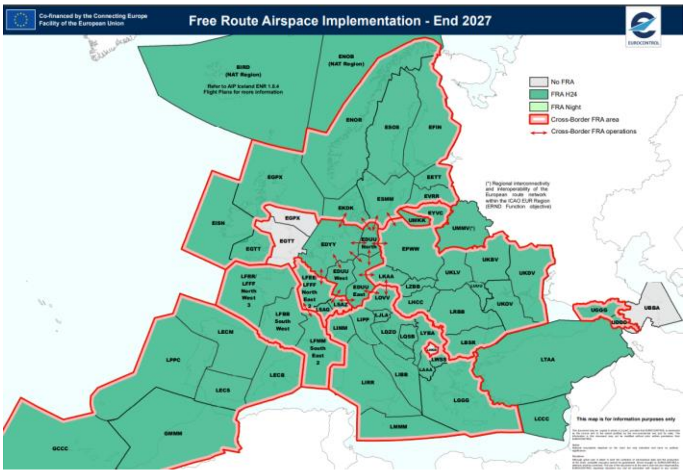

Fig 1.4 Free Route Airspace Implementation - End 2027

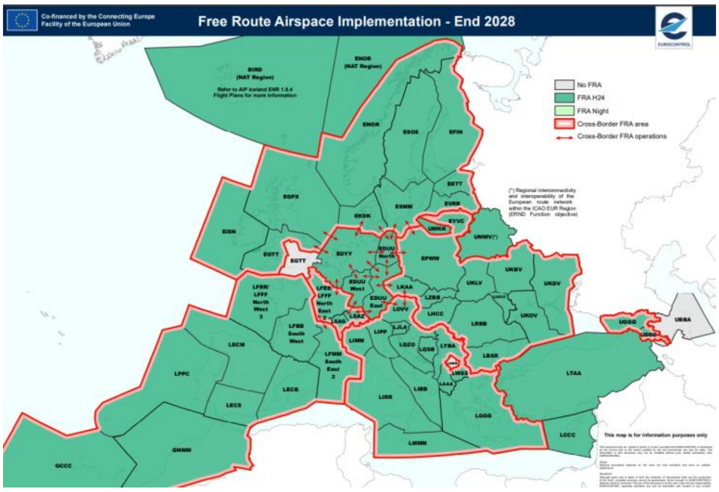

Fig 1.5 Free Route Airspace Implementation - End 2028

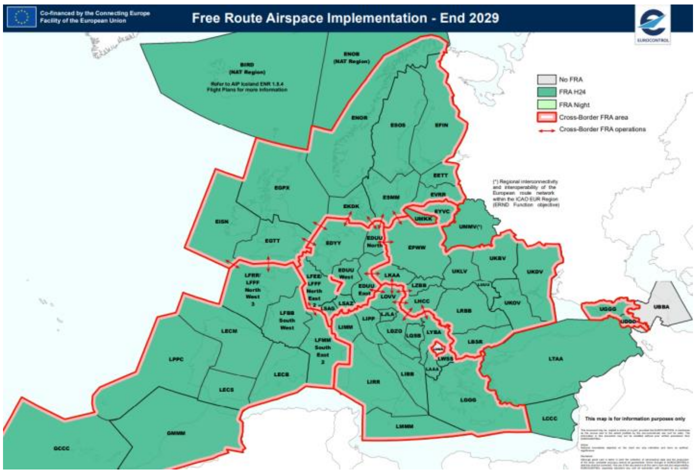

Fig 1.6 Free Route Airspace Implementation - End 2029