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Flight Efficiency Evaluation Tool for Airspace Design

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

Pelo mundo inteiro, a aviação tem desempenhado um importante papel nas deslocções de milhões de pessoas, o que associado a ser o transporte mais rápido e seguro existente, tem levado a um crescimento acentuado do tráfego aéreo nos últimos anos e uma conseqüente pressão acrescida sobre os prestadores destes serviços.

Este documento apresenta, assim, o trabalho desenvolvido no âmbito da tese de mestrado “Flight Efficiency Evaluation Tool”. O objetivo deste projeto é criar uma ferramenta que, recebendo dados de um utilizador, por exemplo um projetista de espaço aéreo, consiga gerar informação relevante para a avaliação de rotas em termos de frequência de utilização, distância, custos, atrasos e sectores cruzados, que permitam ajudar a criar percursos mais eficientes, curtos e baratos e assim otimizar a atual rede de rotas disponíveis. Para tal, essa ferramenta deverá ter acesso a uma base de dados contendo informação respeitante a voos já realizados, a partir da qual gerará dados estatísticos e testará possíveis novas rotas nunca antes utilizadas, conforme a vontade do utilizador.

Após concluído a fase inicial do programa, e realizados vários testes, foi possível verificar que apesar de cada rota ser influenciada por múltiplos factores, com o desempenho desta ferramenta torna-se muito mais simples para o projetista determinar quais as rotas menos eficientes de forma a evitar a acumulação de atrasos e cancelamentos de voos e ao mesmo tempo criar rotas mais eficientes e reduzir o impacto ambiental por elas criado.

Palavras-chave: Avaliação de Rotas, Optimização de Rotas, Desenho de Espaço Aéreo, Análise Estatística.

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Abstract

Around the world, aviation has played an important role in the travel of millions of people, which coupled with being the fastest and safest transport available, has led to a sharp growth in air traffic in the recent years and a consequently increased pressure on the air navigation service providers.

This document presents the work developed on the scope of the master's thesis "Flight Efficiency Evaluation Tool". The aim of this project is to create a tool that, by receiving data from a user, for example an airspace designer, can generate relevant information for route evaluation in terms of frequency of use, distance, costs, delays or even sectors crossed and therefore help to create more efficient, shorter and cheaper routes, optimizing the current network of available routes. To do so, this tool shall have access to a database containing information about past flights, from which it will generate statistical data and test possible new routes never used before.

After completing the initial phase of the program and perform several tests, it was concluded that although each route is influenced by multiple factors, the utilization of this tool makes it much simpler for the designer to determine which routes are less efficient in order to avoid the accumulation of flight delays and cancellations while creating more efficient routes and reducing their environmental impact.

Keywords: Route Evaluation, Route Optimization, Airspace Design, Statistical Analysis.

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Acronyms

AIRAC	Aeronautical Information Regulation and Control
AIS	Aeronautical Information Services
ANSP	Air Navigation Service Providers
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
CFMU	Central Flow Management Unit
CRCO	Central Route Charges Office
DDR	Demand Data Repository
EOBT	Estimated Off-Block Time
ETA	Estimated Time of Arrival
ETS	Emissions Trading System
FAA	Federal Aviation Administration
FIR	Flight Information Region
GUI	Graphic User Interface
ICAO	International Civil Aviation Organization
MTOW	Maximum Take-Off Weight
NMOC	Network Manager's Operations Centre
RP	Reference Period
SESAR	Single European Sky ATM Research
SET	Small Emitters Tool
TMA	Terminal Manoeuvring Area
WF	Weight Factor

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Symbols

d	Distance
r	Radius of Earth
ϕ	Longitude
ψ	Latitude

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Chapter 1

Introduction

1.1 Motivation

Since 1783, with the first manned flight, it became necessary to implement methods to control the interaction, both in mid-air, take-off, landing or ground between flying vehicles. This need led to the development of an Air Traffic Control System which main objective was to prevent collisions between operating aircraft as well as organise and expedite the traffic flow [1]. However, with the continuing forecasted increase of flights in all European Airspace, as shown in the figure 1.1, the Air Navigation Service Providers (ANSP) had to evolve and invest in new technologies and operational procedures in order to comply with this increasing demand.

Since then, multiple measures have been implemented in order to allow a continuous improvement of the Air Traffic Services. Despite all these measures and the significant improvements, “Europe’s air traffic system is struggling to cope with the ever-increasing volume of traffic and other disruptions”, said Violeta Bulc, European Commissioner for Transport at the December 2018 meeting of the European Transport Council. “Last summer passengers experienced unprecedented delays and cancellations. Urgent action is needed in the short, medium and long term. This is the collective responsibility of the European institutions and all aviation stakeholders” [2].

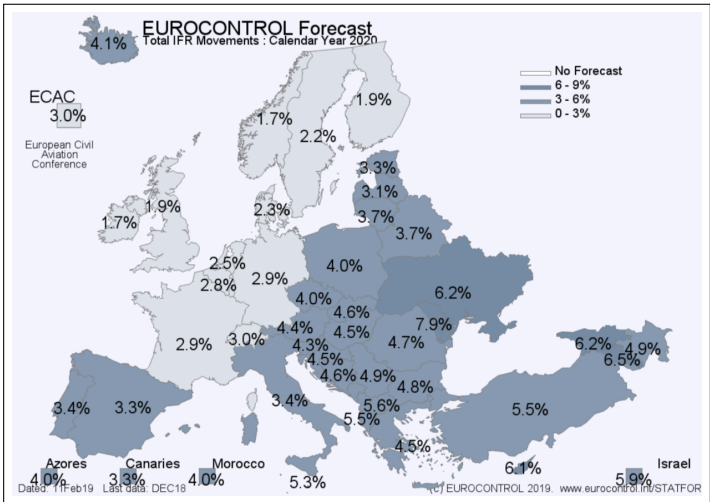


Figure 1.1: Flight Forecast Details for 2020 [6]

Many strategies and programs started to be applied in order to try to keep up with the increasing traffic, such as the Single European Sky ATM Research (SESAR) program.

The SESAR program aims to the combination of increased automation with new strategies to achieve safety, economic, capacity, environmental and security benefits [3]. Also, an important initiative to improve efficiency and, at the same time, the environment was the Free Route Airspace (FRA), which consists in having a joint airspace where users can freely plan their routes, as long as they enter and leave that specific airspace in pre-defined waypoints, continuing subjected to air traffic control [4]. Free route airspace projects are now in place in a large part of european airspace.

Another way of improving the airspace design and the one that will be subjected to study in this thesis is by looking at the Eurocontrol Route Network, as represented in the following figure:

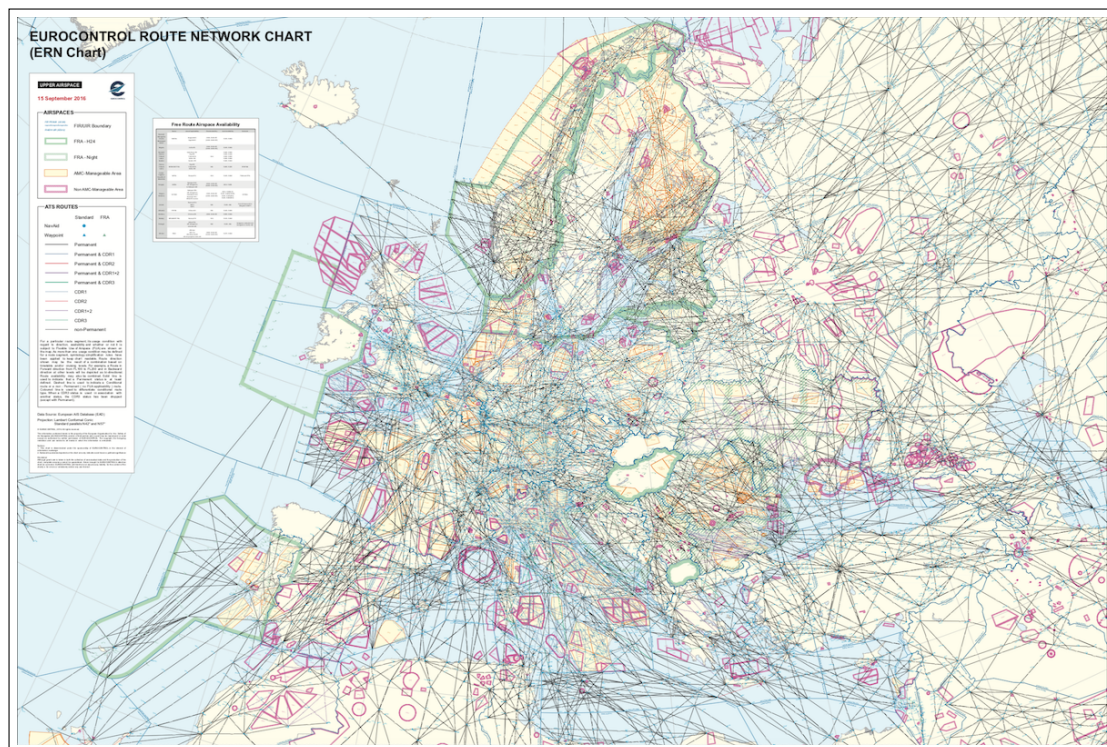


Figure 1.2: Eurocontrol Route Network [5].

Every day in Europe, around 30.000 aircraft are subjected to different planned routes which shall be followed in order to arrive at the destination. There are plenty of different options for airlines to choose their flight plans taking into consideration the airspace structure designed by ANSPs. However, even with the possibility to choose the route for each flight, there are always changes to that route in mid-air, due to constraints in the airspace, such as overloaded sectors, ATC restrictions, or weather. Some constraints don't occur regularly such as weather restrictions, for example, but others such as sector or ATC capacity restrictions can be regular and more common in some sectors than others. If well predicted, it could be possible to avoid these sectors and plan beforehand better routes, which could prevent delays before and during flight.

1.2 Objectives

As was seen before, the European Airspace presents some inefficiencies which leads to several minutes of delay in each flight and some millions of minutes every year. This is an huge drawback to the aviation sector, since it causes money losses to airlines and other dependent companies as well as displeasure to the millions of passengers.

Having that in mind, the goal of this thesis is to develop a Flight Planning Support Tool for Airspace Design that will allow to gather information about past flights, such as routes submitted in the flight plans, real routes used during flight, sectors crossed, among other relevant data and compare them. After that, those trajectories shall be evaluated from a performance point of view, taking into consideration the indicators mentioned, in order to determine the best routes available in terms of distance and CRCO cost.

The tool shall also be able to accept new routes, not existent in the databases, calculate the performance of each new proposal and compare it with the current routes available. In the end, two different files may be created. An excel file to present all that information as a comparison, and a ".kml" file to allow a better visualization of the main routes used and the new routes that may be created and analysed.

1.3 Thesis Outline

The present work is organized as follows:

- In Chapter 1, a brief introduction is given about the main topic and about the goals aimed for this master thesis;
- In Chapter 2, is contained the theoretical concepts needed for the correct understanding of this thesis and the work developed.
- In Chapter 3, the mathematical concepts, algorithms and assumptions taken to develop this thesis will be presented in detail, which will be useful to understand how the program works.
- In Chapter 4, all details about the Application Tool will be described such as the database structure, with all the tables necessary to be created and the files required to be imported to them. Also, will be described the operation of the application itself, which was developed using C++ in the Visual Studio IDE and in the end, the development of the Graphic User Interface with Windows form, in order to create a more attractive environment for the user.
- In Chapter 5, and after having the program totally explained, different case studies are done in order to apply the tool results to the real world and validate them.

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Chapter 2

Air Traffic Management Fundamentals

Air Traffic Management started with the purpose of preventing mid-air collisions between aircraft and simultaneously organize and control the flow in every airspace or airport/aerodrome. To better understand how the tool will work and what has to be taken into consideration to evaluate routes, a knowledge of the following concepts is needed.

2.1 Flight Planning

In modern airspace, every aircraft that may need the assistance of Air Traffic Services must submit a Flight Plan, before taking off, to the EUROCONTROL Network Manager's Operations Centre (NMOC). Those should be submitted at least 3 hours before the Estimated Off-Block Time (EOBT) and up to a maximum of 5 days, prior to the flight day [7]. It establishes the path that the aircraft is expected to follow during the flight, the Estimated Time of Arrival (ETA), the used Flight Rules, among other important information needed for the safety of air navigation.

Although before flight, the planned route must be always submitted as a declaration of intentions for the flight, while en-route, it can be changed by direct request of the pilots to the ATC or by the ATC themselves due to changes in the airspace scenario, like bad weather, sector congestion or others. The route considered by the CRCO to perform the navigation charges calculations is the route submitted in the flight plan. The study of the actual routes is also important since it can show if a determined planned route is not efficient enough and therefore force the pilots/ATC to change it. The main information about each flight, necessary to be uploaded to the developed tool, is mainly stored by Eurocontrol in a database called Demand Data Repository (DDR).

2.2 Demand Data Repository

The DDR is a database held by EUROCONTROL whose objectives are to "provide an accurate picture of pan-European air traffic demand, past and future, from several years ahead until the day before operations. It can be used to support the Network Collaborative Planning Process: strategic, seasonal and pre-tactical planning as well as for the planning of special events or major ATM evolution projects" [8].

It has several useful tools such as [9]:

- Historical Traffic, where it is possible to download historical data from flight plans, actual flown trajectories and flight informations;
- Filtered Traffic, in which is allowed to download data from specific time intervals and with the intended filters;
- Airline Trajectories, useful for flight planning improvement, since it is possible to compare planned and actual routes between the same points and get more specific information about those flights;
- Dataset Files, also very useful for the development of this thesis since it's where it is possible to download information about Airspace Structure, Unit Rates, Waypoints, Airport's Location, among others.

In the figure below is presented the main page of DDR where all the functions described above can be performed.

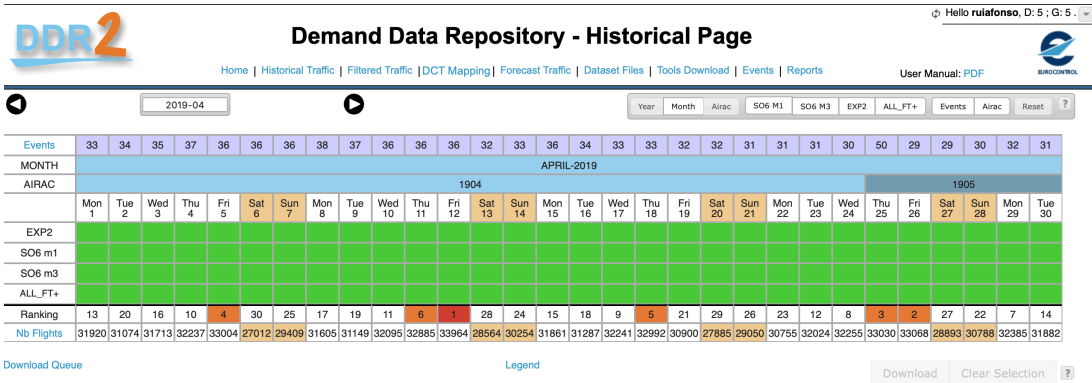


Figure 2.1: DDR database [10].

2.2.1 AIRAC Cycle

An AIRAC Cycle is specified on ICAO's Annex 15 - Aeronautical Information Services (AIS) and stands for Aeronautical Information Regulation and Control (AIRAC). Contains an association of data and standard aeronautical information such that all parties involved in the aeronautical field can have access to the same information base. Was adopted by ICAO in 1964 and defines a series of common dates and an associated standard aeronautical information publication procedure for States [11]. Past traffic and environment data for European Airspace can be downloaded from DDR for each AIRAC.

2.2.2 CRCO Charges

The Central Route Charges Office (CRCO) was created in order to provide an easier and more reliable system of collecting and distributing the en-route charges paid by airlines to EUROCONTROL on behalf of its member states and with that, finance the Air Traffic Management System of the European Airspace [12]. This subject is one of the most fundamental aspects of the planning tool created during this thesis, and therefore will be described with more detail. Each airspace has a specific Unit Rate, which is a factor, in euros, that is multiplied by the weight factor of each aircraft and the corresponding airspace flown distance, to give the route charge as per the following equation:

$$CRCO\ Charge = UnitRate \times WeightFactor \times DistanceFactor \quad (2.1)$$

This operation must be repeated for each charging zone crossed by the route determined in the flight plan. In the middle of each month, every airline must proceed to the respective payments which will after be distributed by the CRCO to every Air Navigation Service Providers (ANSP) from member states.

2.2.2.1 Distance Factor

The Distance Factor is given by the great circle distance (in km) between the entry and exit point on each charging zone. This distance is divided by 100 and in the charging zones that contain the aerodromes of arrival or departure, 20km must be deducted from the total distance flown in the respective charging zones, acting as a corrective factor. The trajectory considered to determine the distance flown in each airspace is determined by the last submitted flight plan, being necessary to the operator to ensure that the informations given in the flight plan correctly reflect the operational intentions of that flight.

In case the initial and final destination of a flight is the same and the respective charging zone is not exited, the distance considered for the calculations is got by reference to the most distant point from the aerodrome.

2.2.2.2 Weight Factor

Regarding the Weight Factor (WF), all airspace users are requested to declare the Maximum Take-Off Weight (MTOW) of the aircraft for each flight. In case of multiple certified MTOWs, only the highest one should be declared. This information is also in the Flight Plan and any changes in this value or in the fleet's composition, such as the acquisition of new aircraft, must be notified to the CRCO as soon as possible.

This factor is expressed with two decimals and is determined by taking the square root of the division by fifty (50) of the MTOW (in Tons), as is represented in the equation below:

$$WF = \sqrt{\frac{MTOW}{50}} \quad (2.2)$$

All aircraft operated by an airline, even if on lease from another airline, must be present in the fleet declaration submitted to the Eurocontrol CRCO, as well as the next items:

- The aircraft type;
- The respective version, within the type;
- The construction number (MSN);
- The mode "S";
- The exact highest certified MTOW (in kg).

This information can be sent by email to the CRCO.

2.2.2.3 Unit Rate

The Unit Rate is the charge, in euros, applied to any flight if it is done by a 50 metric tonne aircraft (correspondent to a weight factor of 1.00) and in which the distance factor is 1.00. It is used to compute the total applied charge for each flight. The unit rates can be adjusted every month in accordance with the exchange rate fluctuations. The countries' respective unit rates can be consulted in the Eurocontrol public website [13].

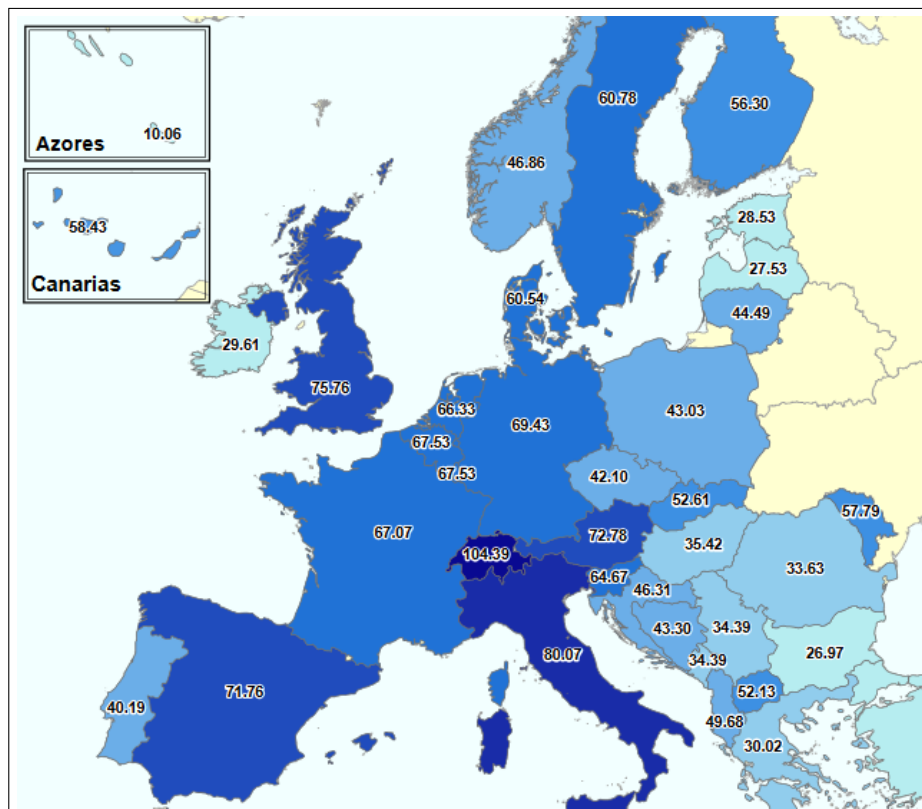


Figure 2.2: Example of distribution of Unit Rates by country [14].

2.2.3 Delay by Regulation

A Regulation is a preventive measure applied by ANSPs in order to avoid en-route traffic overloads. This measure is based on the assumption that is cheaper and safer to hold on the ground than en-route [15]. The airspace is divided into Flight Information Regions (FIR), divisions in airspace with the same operating conditions in order to facilitate the application of air navigation services [16], which are in turn, divided into sectors and airblocks. Each sector has a declared capacity established by the Central Flow Management Unit (CFMU) which represents the number of aircraft that can be flying that sector at a certain time. This capacity could be reduced depending on multiple factors, such as bad weather in a certain period of the day, Air Traffic Control Services available for each sector, closed airspace due to, for example, military activities, among others. When one of these perturbations are affecting a sector, a regulation is applied reducing the capacity of that specific sector, to prevent any problem. Other factors that have a major contribution to delay can be due to the airlines themselves and their customer services. The influence of these factors in the average delay per flight is presented below:

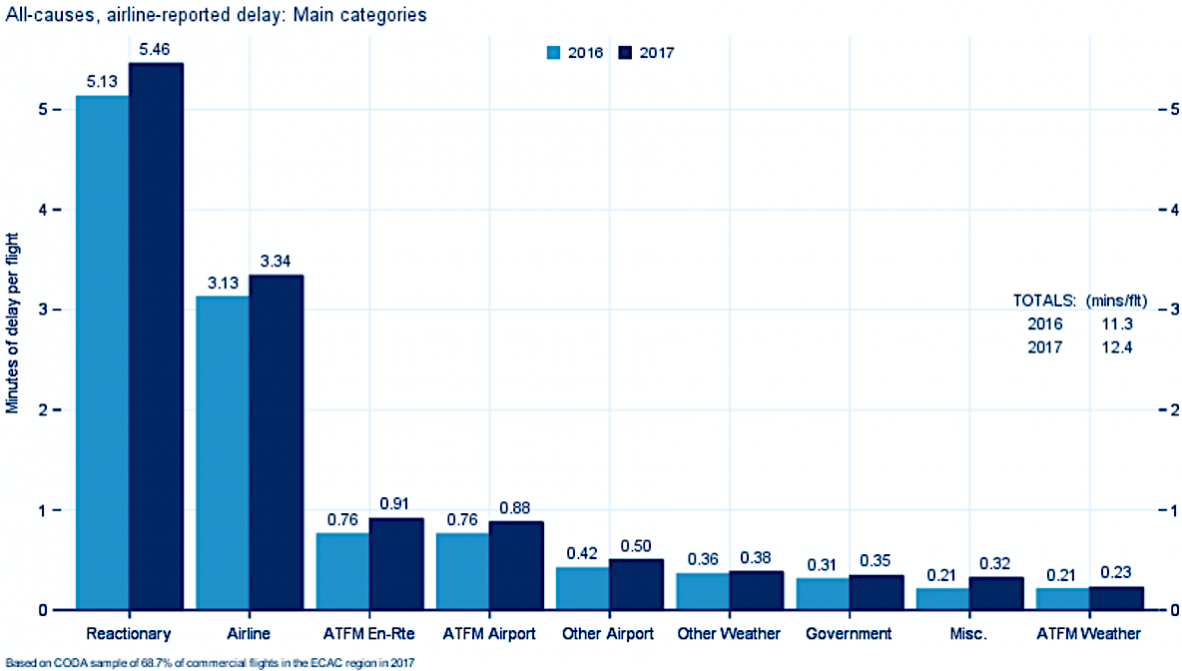


Figure 2.3: All Causes, Airline-Reported Delay: Main Categories [17].

As it can be seen, the major contributions to flight delays are induced by Airlines, due to bureaucracies or operational strategies and by the Reactionary Delay (Cumulative delay during the day). However, in the scope of this thesis, only en-route sources of delay, such as from Air Traffic Flow Management (ATFM) or Weather, will be taken into consideration for the development of the Flight Planning Support Tool.

The objective is to detect the most affected sectors and the main routes that cross them, in order to create new routes that can avoid those congested areas saving time and money, decreasing the overall delay.

2.2.4 Environmental Impact of Aviation

With the continuous growth of the number of flights per year, the consequent fuel consumption has increased and with it, the emission of gases like CO_2 , NO_x or water vapour. Also, numerous other chemicals and microscopic particles that can affect the climate are released having a negative impact on the environment such as the formation of tropospheric ozone (O_3), formation of condensation trails (contrails) and cirrus clouds [18].

Since the awareness for global warming has been growing, in 2001 ICAO endorsed the development of an open emissions trading system (ETS) for aviation, in which the airlines are induced to reduce their emissions [19].

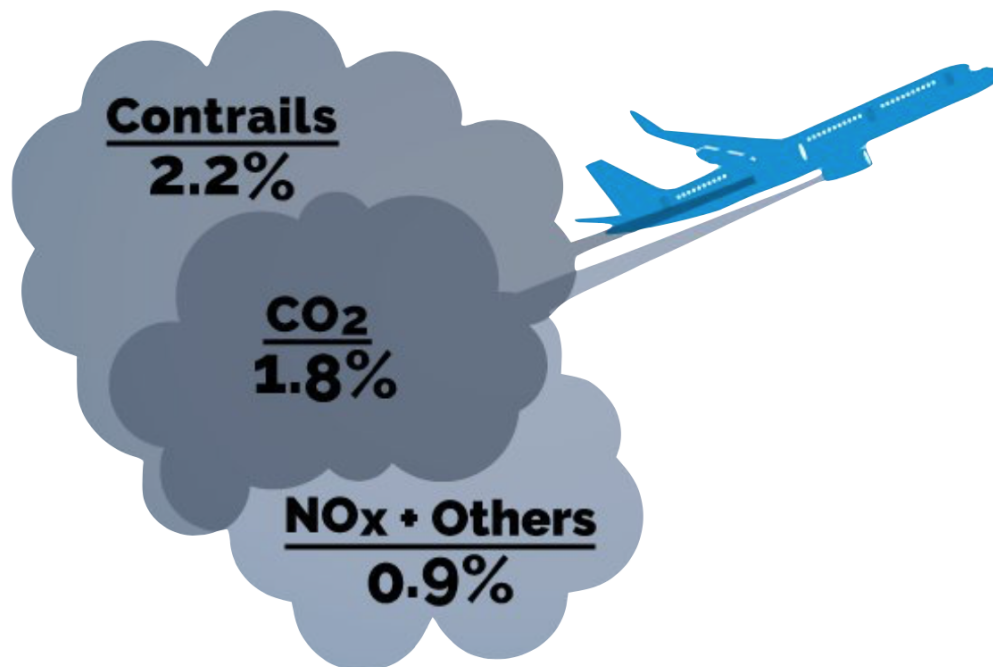


Figure 2.4: Impact of aircraft emissions on global warming. (Lee and Fahey, 2009)

Most of these gases have a stronger impact if released at higher altitudes, meaning that it is relevant to try to reduce the en-route gases. According to "Aviation Emissions, Impacts & Mitigation: A Primer" published by the FAA's Office of Environment and Energy [20], one of the possible ways to reduce this harmful release of gases is by reducing the flight time. This can be achieved by changing the actual route network, creating new and more optimized routes that could lead to reduced flight distances. This is exactly the aim of this thesis since with the program developed it is expected to gain access to a detailed historical database of current flown routes and their characteristics. With this, it is expected to determine which ones are more or less efficient in order to design new routes and consequently reduce the emission of gases.

As was seen above, there are numerous factors that affect the performance of a specific route. However, when analysing the route network optimisation criteria, the environmental impact is not always given as much importance as it should. In each flight, the ATC can allow a direct route or, due to occasional constraints, such as dense traffic, weather or military zones, force the pilot to fly longer distances leading to extra delays and therefore extra fuel consumption. This extra fuel burnt on the upper atmosphere and near the airports have a detrimental effect to the environment. When extrapolating this assumption to the thousand flights per day, it becomes evident that it has a huge impact on the environment.

Several studies have been conducted, such as the “Flight Efficiency and Impact on Environment” [21], in order to develop indicators that could serve as a measuring tool to determine the environmental impact of the ATM System. Their objective is to determine the efficiency of the actual network of routes in what concerns to distance, fuel burn, flight duration, among others. These indicators are mainly used by the EUROCONTROL Performance Review Commission for its annual performance review report of air traffic management in Europe [21].

Currently, airlines have a different number of tools to help determine the environmental impact of each flight. These tools have a huge impact on the flight planning operations since each airline has to fulfil a specific percentage of emissions per year, represented in the respective Reference Period (RP). One of those tools, most commonly used by airlines, is the Small Emitters Tool (SET) by EUROCONTROL which allows estimating the amount of fuel burnt and CO₂ emitted in each flight considering multiple factors such as type of aircraft, distance flown and the characteristics of the air traffic covered by the EU Emissions Trading Scheme (EU ETS).

2	Select distance unit for City pair distance						
3	Kilometer						
5				Total Nb of flights	Total Estimated fuel	Total Estimated CO2	
6				42	313 401	987 214	
7							
8	Input parameters						
9	ICAO Aircraft Type	City pair flown	Nb of flights	Add 95km(51NM)	Estimated Fuel	Estimated CO2	
	Designator	distance			(Kg)	(Kg)	
22	B734	3 117	1	Y	11 532	36 326	
23	B737	1 876	1	Y	6 272	19 757	
24	B738	2 752	1	Y	9 436	29 723	
25	B752	2 771	1	Y	13 134	41 372	
26	B763	2 974	1	Y	18 849	59 374	
27	B772	2 771	1	Y	24 104	75 928	
28	E190	2 750	1	Y	7 550	23 783	
29	E195	1 863	1	Y	5 756	18 131	
30	MD83	2 324	1	Y	10 084	31 765	
31	A20N	220	1	Y	1 001	3 153	
32	A21N	220	1	Y	1 239	3 903	
33	A319	26	1	Y	1 200	3 780	
34	A320	26	1	Y	1 271	4 004	
35	A321	26	1	Y	1 389	4 375	
36	A332	220	1	Y	3 375	10 631	
37	A333	220	1	Y	3 447	10 858	
38	A339	1 032	1	Y	9 545	30 067	
39	A343	130	1	Y	3 307	10 417	

Figure 2.5: Example of the SET tool.

The algorithm that is used to compute the Estimated Fuel and Emitted CO₂ in the SET is also incorporated in the FPST in order to allow to compute the average fuel consumption of the routes in study and help the airspace designers or end users of the FPST to estimate the environmental impact of the designed routes.

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Chapter 3

Mathematical Background

In this chapter, the mathematical concepts and algorithms needed to determine the intersections between routes and FIR's borders will be presented.

3.1 Initial Assumptions

For the development of this thesis, calculations regarding orthodromic lines, intersection of different segments characterized by latitude and longitude coordinates and route costs will be used. Therefore, and in order to comply with the regulations established by EUROCONTROL and the Central Route Charges Office, the methods to determine those costs will be the same as the ones used by the CRCO. Other assumptions used:

- The Earth is considered as a sphere with radius equal to 6371.0 km;
- The distances determined in the following calculations are related to the surface of the Earth, assuming that the differences in altitude can be neglected for simplicity of calculations;
- For each take-off or landing in a charging zone, 20 km are deducted from the total distance for that charging zone [12].

3.2 Great and Small Circle Distances

Starting with the spherical earth assumption and knowing that the points in study for each route will be given in a latitude/longitude coordinate system, a method to determine the length of a segment between two points must be found. When dealing with flight routes, the smallest path between two points is not the direct line, but the arc formed by those two sets of coordinates on the surface of the Earth when assuming the intersection between the surface of the sphere and a plane that crosses the center of that sphere. This arc is called a "great circle". The arc that cuts the sphere but does not cross its center, is called "small circle" [22]. A representation of these circles can be seen in the Figure 3.1.

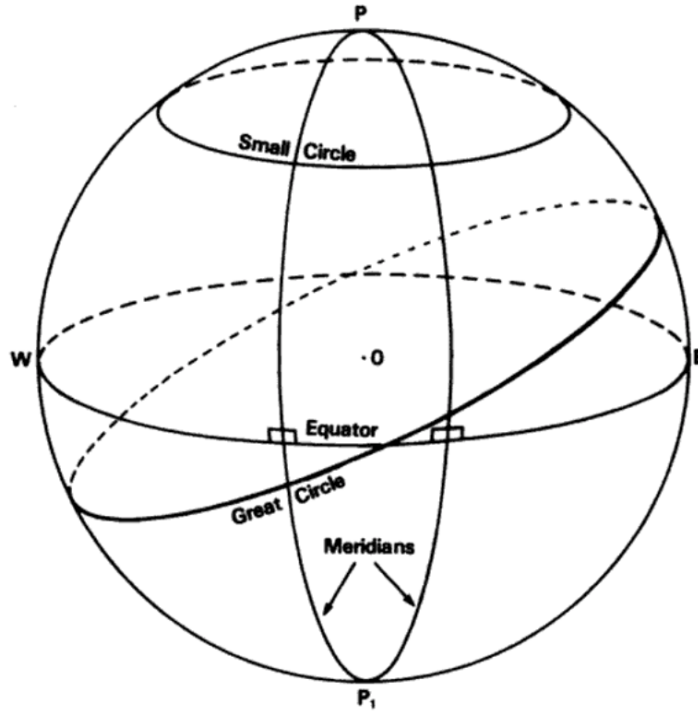


Figure 3.1: Representation of small and great circles [24].

So, in order to determine the shortest distance between two points, the Haversine Formula was used.

3.2.1 Haversine Formula

The Haversine formula is an important equation in navigation that gives the shortest distance between two sets of points in a sphere's surface knowing their latitude and longitude, as follows [23]:

$$d = 2r \sin^{-1} \left(\sqrt{\sin^2 \left(\frac{\phi_2 - \phi_1}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left(\frac{\psi_2 - \psi_1}{2} \right)} \right) \quad (3.1)$$

,where:

d is the distance, in km;

r is the radius of Earth, in km;

ψ_1, ψ_2 are the latitudes of initial and ending points, respectively, in radians;

ϕ_1, ϕ_2 are the longitudes of initial and ending points, respectively, in radians;

3.3 Great Circle Arcs Intersection Algorithm

Having the formula to determine the distance between two points, it becomes necessary to have a method that can determine if two segments intersect. If they do, the coordinates of the intersection point have to be determined in order to detect when and where a route changes charging zone. That leads to the following algorithm [24]:

Considering two great circle arcs in a sphere, arc a from a_0 to a_1 and arc b from b_0 to b_1 . Both points are characterized by latitude, ϕ , (positive in the North direction) and longitude, θ , (positive in the East direction from Greenwich).

The first step of the algorithm is to transform these coordinates into Cartesian Coordinates, using the following equations:

$$\begin{aligned}x &= \cos(\theta)\cos(\phi) \\y &= \sin(\theta)\cos(\phi) \\z &= \sin(\phi)\end{aligned}\tag{3.2}$$

where,

$$\begin{aligned}-\pi &\leq \theta \leq \pi \\-\frac{\pi}{2} &\leq \phi \leq \frac{\pi}{2}\end{aligned}$$

Assuming \vec{a}_0 , \vec{a}_1 , \vec{b}_0 and \vec{b}_1 to be vectors of the Cartesian coordinate endpoints for both arcs a and b , the subsequent computations may be taken:

- $\vec{p} = \vec{a}_0 \times \vec{a}_1$ is the vector normal to the plane that contains the arc a and crosses the centre of the Earth;
- $\vec{q} = \vec{b}_0 \times \vec{b}_1$ is the vector normal to the plane that contains the arc b and crosses the centre of the Earth;
- $\vec{t} = \frac{\vec{p} \times \vec{q}}{\|\vec{p} \times \vec{q}\|}$ is along the line of intersection of both planes.

Then, the following quantities can be defined, which represent the t projection along the arcs a and b :

$$\begin{aligned}s_1 &= (\vec{a}_0 \times \vec{p}) \cdot \vec{t} \\s_2 &= (\vec{a}_1 \times \vec{p}) \cdot \vec{t} \\s_3 &= (\vec{b}_0 \times \vec{q}) \cdot \vec{t} \\s_4 &= (\vec{b}_1 \times \vec{q}) \cdot \vec{t}\end{aligned}\tag{3.3}$$

In case of having $-s_1$, s_2 , $-s_3$ and s_4 with the same signal, then it means that the arcs intersect. In that case, if the signs are all positive, the intersection will occur along $+t$, if they are all negative, then the intersection occurs along $-t$. Having the intersection confirmed becomes necessary to determine in which coordinates there is intersection, which can be determined by transforming the obtained vector, t , according to the following relations:

$$\begin{aligned}\theta &= \arctan2(y, x) \\ \phi &= \arctan2(z, \sqrt{x^2 + y^2})\end{aligned}\tag{3.4}$$

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Chapter 4

NEST Modelling Tool

The Network Strategic Tool (NEST) is a desktop application that combines the capacities of two pre-existent software, SAAM, which has powerful airspace design capabilities and NEVAC, with capacity analysis functionalities and user-friendliness.

It is a powerful tool that allows the visualization of lots of sorts of data from previous flights, organized in AIRACs. It has multiple advantages since it allows the application of different filters and therefore a better selection of data. To do this, it's possible to import an AIRAC from the DDR and other useful information that will be used as a data source for the developed tool.

After importing the AIRAC, it is possible to explore either the planned flights as the real flown ones for a specific day in the corresponding AIRAC's month. However, only the flights of one day are represented at each time, being a drawback in the case it is intended to analyse a bigger spectrum of flights. In the figure below is presented the main interface of the NEST tool:

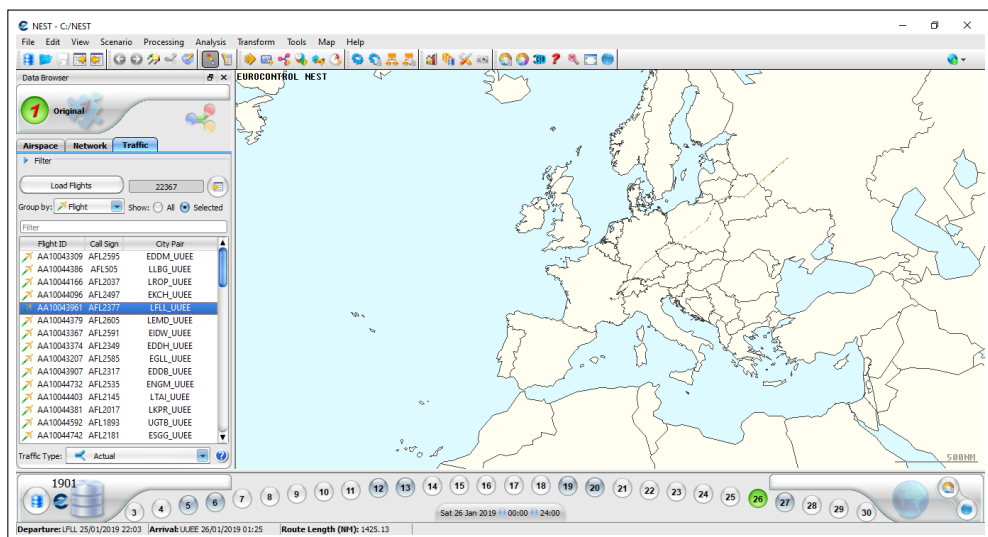


Figure 4.1: NEST Interface.

Also, since each AIRAC contains all flights that entered or exited the European Airspace that is part of EUROCONTROL, the amount of data is very big, having about 30.000 flights per day. So that, it is necessary to apply filters.

4.1 Filters

In order to only obtain the desired data to use in the developed tool (flights that cross the Portuguese and surrounding airspaces) and discard the unnecessary data, is necessary to apply filters to the selected data and therefore reduce by a lot the amount necessary to analyse with the tool, leading to a better performance.

The query used as a filter that translates the mentioned restrictions is presented in the Appendix A. With the application of this query, the number of flights analysed can be reduced from around 30.000 to about 3.000 flights per day, which is very significant. Its objective is to reduce the studied flights to only those that cross the LP Fir and its adjacents, since they are the ones relevant to the scope of this thesis.

So, to better understand how this query has a useful meaning, the resultant flights selected with and without the application of the query is shown in Figures 4.2 and 4.3.

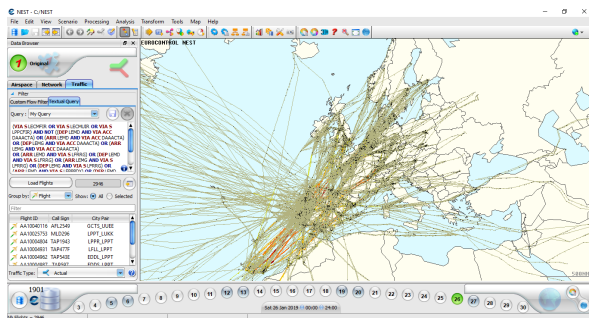


Figure 4.2: Flight routes when applying the intended filters.

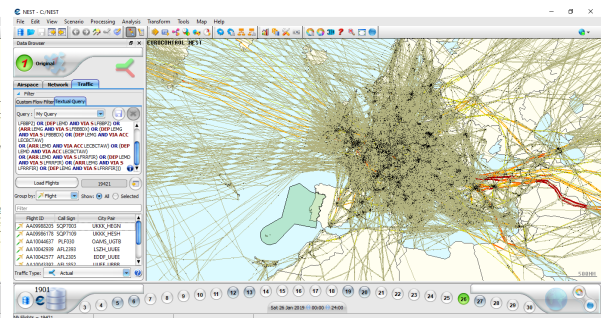


Figure 4.3: Flight routes that are not relevant and therefore discarded.

After having only the flights that respect the requisites to use in the Flight Planning Support Tool (FPST), it is possible to check the main information about each one, which is presented by the software as follows in the Figure 4.4:

Date/Time	Airport	Navigation Point	Flight Level	Latitude	Longitude	Exit Time
25/01/2019 23:56:13	-	*1CIS	50	38°53'11"	-9°00'23"	23:56:13
25/01/2019 23:53:00	LPPT	-	0	38°46'27"	-9°08'03"	23:53:00
26/01/2019 00:05:55	-	IDBID	233	39°16'42"	-8°01'00"	00:05:55
26/01/2019 00:11:10	-	PORLI	290	39°31'44"	-7°21'59"	00:11:10
26/01/2019 00:17:47	-	URED1	341	39°51'35"	-6°23'36"	00:17:47
26/01/2019 00:24:38	-	ZORBA	375	40°11'17"	-5°23'38"	00:24:38
26/01/2019 00:29:34	-	DIPOL	380	40°24'59"	-4°40'35"	00:29:34
26/01/2019 00:39:04	-	RBO	380	40°51'14"	-3°14'48"	00:39:04
26/01/2019 00:43:09	-	PINAR	380	40°58'49"	-2°35'57"	00:43:09
26/01/2019 00:44:39	-	SEGRE	380	41°01'22"	-2°22'35"	00:44:39
26/01/2019 00:46:34	-	BRITO	380	41°04'45"	-2°04'41"	00:46:34
26/01/2019 00:50:41	-	PISUS	380	41°11'37"	-1°27'18"	00:50:41
26/01/2019 00:52:32	-	GOVIG	380	41°14'41"	-1°10'17"	00:52:32
26/01/2019 01:01:26	-	SEROX	380	41°20'48"	0°13'07"	01:01:26
26/01/2019 00:56:35	-	PONEN	380	41°21'14"	-0°32'51"	00:56:35
26/01/2019 01:25:02	-	MAROT	380	41°36'20"	3°51'37"	01:25:02
26/01/2019 01:35:56	-	NEVIX	385	42°24'51"	5°03'42"	01:35:56
26/01/2019 01:49:00	-	STP	390	43°13'10"	6°36'07"	01:49:00
26/01/2019 01:51:04	-	TUXT	390	43°20'46"	6°50'30"	01:51:04
26/01/2019 01:51:31	-	RAPED	390	43°22'24"	6°53'36"	01:51:31

Figure 4.4: Detailed information about a specific flight.

Here is shown the detailed information about each flight and that can after be exported as a ".so6" file that will after be uploaded into the developed FPST as will be described in detail in the next chapters. A major drawback and one of the most fundamental aspects that led to the development of the FPST is that it is only possible to analyse one flight at a time, being very difficult to use this information as a comparative method to study the best routes and other aspects that may be useful for the ANSPs.

4.2 Delay by Regulation

Another useful information that can be retrieved from NEST is the Delay induced in each flight by Regulations imposed by ANSPs when a certain sector is being affected by any perturbation, such as Weather, lack of ATC personnel, Aerodrome or Airspace Capacity.

This kind of delay is one of the major causes of flight delays and therefore an important detail to study with this project, by trying to find the most frequent sectors that are affected by this type of delay and therefore try to avoid them. It could allow saving dozens of minutes per flight leading to less cumulative delay during each day.

Those informations can be exported by selecting the "Statistics" tab and then choosing in the "Type" section, "Regulations", as shown below in Figure 4.5:

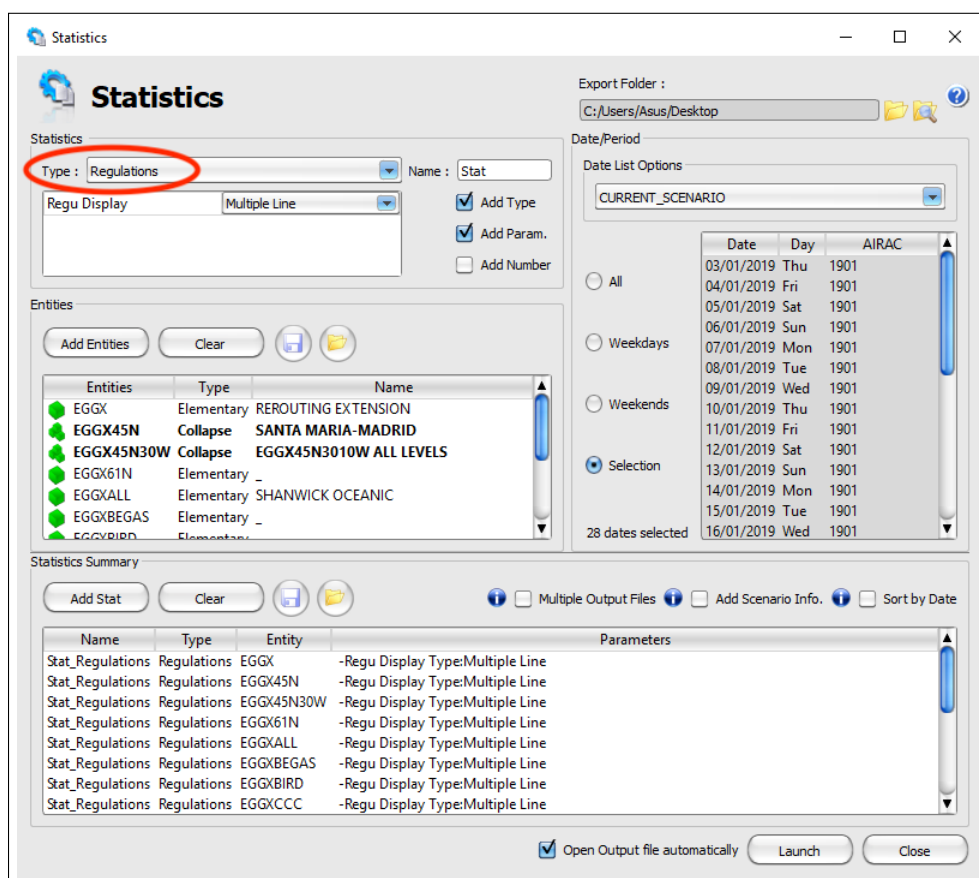


Figure 4.5: Exporting data regarding Delays by Regulation.

After selecting the desired airspace in the "Entities" section and the Period of time, in the "Date/Period" tab, it can be exported as an excel file. This file contains multiple information, such as the day in which the regulations took place, the sectors or airports affected, the total delay associated with the respective airport or sector and their capacity during that interval. In the figure below is a representation of the exported excel. (Some columns were hidden to allow a better visualization of how data is organized):

	A	C	E	F	G	H	J	O	P	Q	R
1	date	airspace type	regu ID	TV ID	Ref. Loc. ID	Ref. Loc. Type	total delay (mins)	Reason	Start	End	Capacity
2	26/01/2019	ECAC Area	EDDPA25	EDDPARR	EDDP	Airport	26	WEATHER	22:00	00:39	20
3	26/01/2019	ECAC Area	EDWSU25N	EDWWSUDN	EDWWSOUTH	Sector	56	ATC CAPACITY	23:20	00:39	16
4	26/01/2019	ECAC Area	EBLGA25	EBLGARR	EBLG	Airport	179	WEATHER	23:00	00:59	14
5	26/01/2019	ECAC Area	LLBGA25N	LLBGARRS	LLBG	Airport	0	AERODROME CAPACITY	23:50	23:59	18
6	26/01/2019	ECAC Area	LLBGA25N	LLBGARRS	LLBG	Airport	0	AERODROME CAPACITY	00:00	00:59	21
7	26/01/2019	ECAC Area	LQTZG25N	LQTZ	LQTZ	Airport	0	ATC STAFFING	23:30	04:59	0
8	26/01/2019	ECAC Area	LTBAA26M	LTBAARR	LTBA	Airport	284	WEATHER	03:00	05:19	28
9	26/01/2019	ECAC Area	LFPOA26	LFPOARR2	LFPO	Airport	9	AERODROME CAPACITY	06:00	06:09	25
10	26/01/2019	ECAC Area	ESE26E	LFE5E	LFE5E	Sector	56	ATC STAFFING	05:20	06:19	32
11	26/01/2019	ECAC Area	ESE26E	LFE5E	LFE5E	Sector	0	ATC STAFFING	06:20	06:59	70
12	26/01/2019	ECAC Area	ETOPON26	LFETOPON	LFEE5R	Sector	4	ATC CAPACITY	05:20	06:59	30
13	26/01/2019	ECAC Area	ETORES26	LFETORES	LFEE5R	Sector	81	ATC CAPACITY	05:20	06:59	35
14	26/01/2019	ECAC Area	KFFM126M	EDUFFM1C	EDUUFFM1C	Sector	82	ATC CAPACITY	06:00	06:59	50
15	26/01/2019	ECAC Area	RR1FTE26	RR1FTE	LFFFTE	Sector	0	ATC CAPACITY	06:20	07:59	0
16	26/01/2019	ECAC Area	RR2FTE26	RR2FTE	LFFFTE	Sector	0	ATC CAPACITY	06:20	07:59	0
17	26/01/2019	ECAC Area	LFOBA26E	LFOBARR	LFOB	Airport	48	WEATHER	07:30	08:15	5
18	26/01/2019	ECAC Area	RR4AST26	RR4AST	LECMASI	Sector	0	ATC CAPACITY	07:00	08:19	0
19	26/01/2019	ECAC Area	KOH26M	EDUOH	EDUOH	Sector	515	ATC STAFFING	05:30	08:39	42
20	26/01/2019	ECAC Area	FL7RVK26	FL7RVK	LFRRVKU	Sector	0	ATC CAPACITY	07:00	08:39	0

Figure 4.6: Example of how data is organized when exported from NEST.

4.3 CRCO Cost

As was discussed previously, the determination of the CRCO costs is a fundamental aspect for the analysis of routes which is the aim of the developed tool. Therefore is essential that the computed costs are correct or as close to the correct values as possible. These values can also be retrieved from NEST for a certain flight or a group of flights. However, it requires multiple operations by the user and gives only that information which is separated from other useful information which, in the end, results in a wide amount of files and disorganised information.

Nevertheless, it is useful for the validation of the values computed by the tool. Therefore, the process to obtain these values from NEST will be presented below:

The first step is to export, as a ".so6" file, the flights that are intended to analyse. Important to mention that the selected "traffic type" shall be the "Initial" Flights, since the CRCO Costs are determined based on the routes submitted in the flight plan. After that, is necessary to obtain an intersection file ".t5". It can be done by choosing the "Processing" tab, then "Airspace/Traffic Intersection" that will open the options

box that generates this file. The ".so6" file exported in the first step must be included as well. Then by pressing the "Run" button the ".t5" file is generated, as shown below:

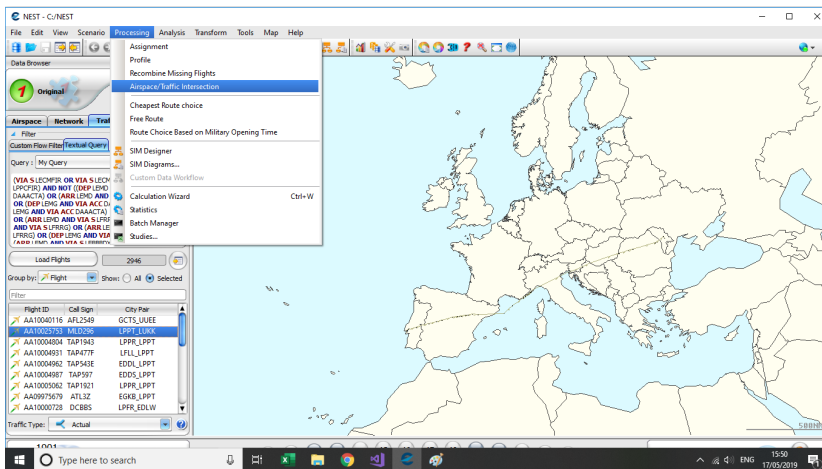


Figure 4.7: Process to obtain the .t5 and .so6 files.

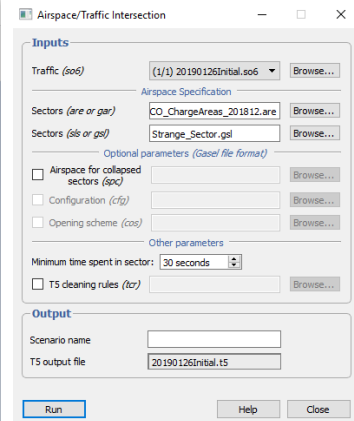


Figure 4.8: Airspace/Traffic Intersection Window.

The next step is then to select the "Analysis" menu and then "Route Charge". Here the previously exported files must be imported in the "Input" section as presented in the following figures:

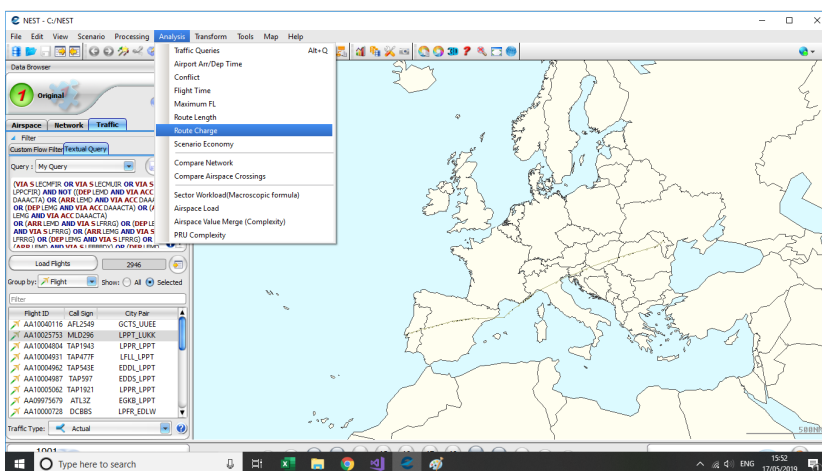


Figure 4.9: Process to obtain the CRCO charges file.

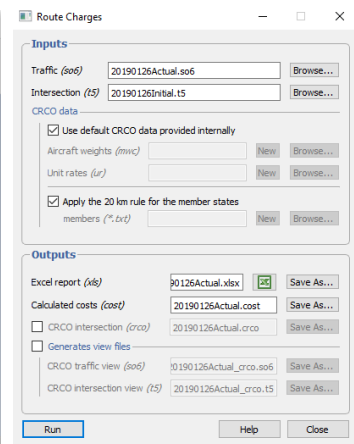


Figure 4.10: Route Charges Window.

After these steps, the output files become available in the NEST's "Import/Export" folder and therefore ready to be imported into the database to be used by the application tool as will be shown in the next chapter.

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Chapter 5

Flight Planning Support Tool

In this chapter, the tools, steps, software and data used to develop the FPST will be presented, as well as how the concepts discussed in the previous chapters have a role in it.

5.1 Initial Considerations

As was mentioned in the previous chapters, the aim of this thesis was the development of a tool that, in order to complement the NEST tool capabilities, would allow to collect only the necessary information from thousands of flights and, after perform multiple necessary calculations, display it in a simplified and more organized way to allow the comparison between different routes chosen from different flights between the same airports or waypoints.

So, for the development of this tool, it was necessary to choose the software that would allow to collect and store big amounts of data as well as manipulate it in order to compute the results. Also, it would be necessary a software for the development of the application itself. Knowing this, the final choice went to Microsoft SQL Server Express, which would allow the storage and manipulation of data and Visual Studio with C++ libraries for the development of the application, as well as Windows Forms for the design of the Graphic User Interface, which are all free and open-source software. Regarding the outputs of the application, it was chosen Excel to organize the results and Google Earth to allow a better visualization, by the user, of the analysed routes as well as the possible new routes created.

The Data is then retrieved from the aforementioned DDR and NEST and exported into a previously created database in SQL Server. To organize the imported data, several tables were also created as will be explained in detail in the following sections.

5.2 Database

Since it is necessary to manipulate and analyse lots of different files with different flight data, they are initially stored in a database created in SQL Server Express named "FPST".

Inside the main database, several tables were then created to store and organize the different types of data. Below, a list of the created tables and the data stored in each will be presented.

5.2.1 Imported Data

First, it was necessary to determine which information would be relevant to use in the tool and that could be exported from DDR and NEST.

From NEST, the following files have to be imported:

- YYYYMMDDInitial.so6 – Contains the general information of the planned flights for a specific day (indicated in the name of each file);
- YYYYMMDDActual.so6 – Contains the general information of the real flights for a specific day (indicated in the name of each file).

It is necessary to export as many of these files as desired. For example, in order to have an one month sample, it is required to export both files 30 times, two for each day. The other source of information, where it is possible to download data is, as mentioned before, DDR. The files that can be exported from it are the following:

- VST_YYMM_Airports.arp – Contains the ICAO code of all airports that belong to the EUROCONTROL Network and their respective coordinates;
- NavPoint_YYYYMM.nnpt – Contains the waypoints available in the EUROCONTROL Network and their respective coordinates;
- CRCO_UnitRates_YYYYMM.ur – Contains the list of charging areas and corresponding unit rates;
- CRCO_AircraftWeights_YYYYMM.mwc – Contains the list of aircraft models and their respective average MTOW, in tons;
- CRCO_ChargeAreas_YYYYMM.are – Contains the boundary points and respective coordinates of the charging areas.

In order for the tool to be able to read all of these files, they shall be stored in the same folder, "C:\NEST \Import_Export".

5.2.2 Data storage

Now that all the required information is collected, it is necessary to find a way to store it all. Therefore, and as mentioned above, it was used SQL Server Express, a free version of Microsoft's SQL Server relational database management system.

5.2.2.1 Info Tables

These tables contain most of the information from the files previously downloaded and are only used to store the bulk data that will be used afterwards. Whenever new files are imported into the "Import/Export" folder, the new data replaces the one previously stored.

- **MAP_DEG:** Contains the information about all EUROCONTROL Network belonging FIRs such as the coordinates that allow drawing each FIR in space;
- **NAV_POINTS:** Contains the data from "Nav-Point_YYYYMM.npt" with the Navigation Points in the European Airspace and their respective coordinates;
- **CRCO_AircraftWeights:** Includes the "CRCO_AircraftWeights_YYYYMM.mwc" file and lists airplane models and their respective average MTOW. Also includes fuel characteristics for fuel consumption analysis;
- **AIRPORTS:** This table is used to store the data from the "VST.YYMM.Airports arp" file that contains most of the European Airport's ICAO codes and respective geographic coordinates;
- **REGULATIONS:** Contains the data related to the regulations applied each day and the reason they were applied;
- **SECTORS:** Contains the coordinates that define the Sectors in some FIRs of the EUROCONTROL Network;
- **CRCO_UnitRates:** Contains the data from the "CRCO_UnitRates_YYYYMM.ur" file such as the list of charging areas.

5.2.2.2 Supplementary Tables

These tables are used as an intermediate step while the data insertion into the "Info Tables" occur and helps the program to understand which files are available and which have already been read.

- **ALLFILENAMES:** This table contains, as mentioned above, the list of files that are available to extract data. If any necessary file is missing, it allows the program to detect it and send an error message, which otherwise would possibly crash the program;
- **TRAJECTORIES:** This is also an auxiliary table used to store the geographic coordinates of all route waypoints for each flight. This information will be later used to draw the route's path in Google Earth, allowing a better visualization and perception of each route.

5.2.2.3 Core Tables

Now the auxiliary data is organized. However, is still necessary to store the data from the "Initial" and "Actual" files. This is the most important data to store since it contains the information about all flights, origin and destination airports, waypoints crossed and so on. So, the following tables were created:

- **SO6_M1(M3):** In these tables is stored the raw data directly extracted from the "initial.so6" and "actual.so6" files. It is organized by flight.id and a "Sequence" column in order to allow to organize the data by Flight ID. It is also organized by days, since, as mentioned before, the tool will require data from multiple days to have a sufficient sample to make conclusions.

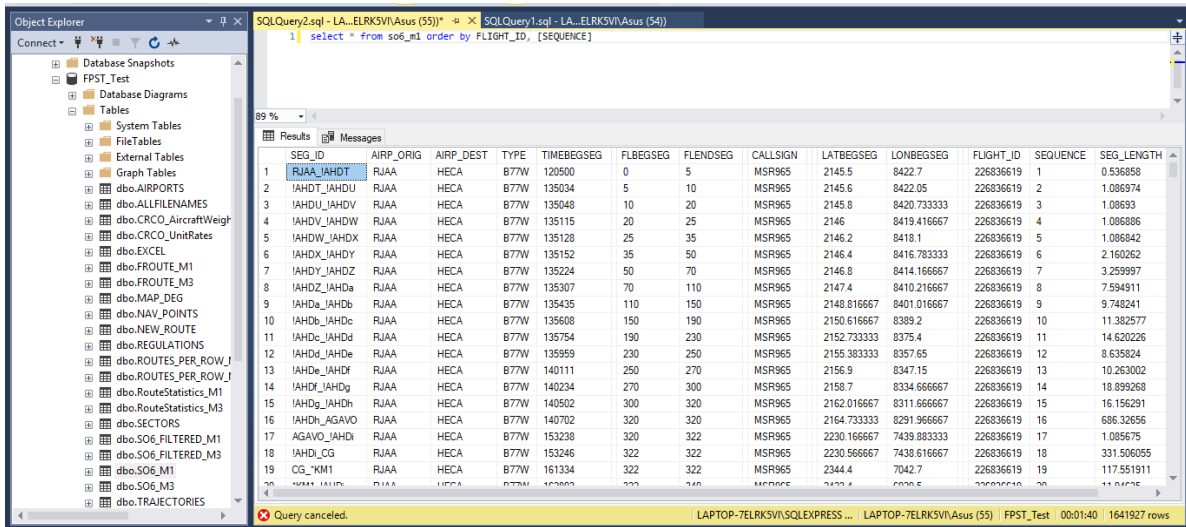


Figure 5.1: Example of how data is stored in SQL Server Express.

However, most of that data is irrelevant and leads to higher processing time, becoming mandatory to "clean" the raw data and get only the relevant information. Therefore some other tables were created to store that "cleaned" information, such as:

- **SO6_FILTERED_M1(M3):** In these tables, the data from SO6_M1(M3) tables is "cleaned", in a way that the SEG.ID entries (as seen in the figure above) are compared to the waypoints contained in the "NAV.POINTS" table and only those that match are maintained. This will remove the auxiliary points created during the flight to store extra information like altitude changes and so on, but that is not relevant to the scope of this project.
- **FRROUTE.M1(M3):** These are even more synthesized tables containing all flights and their respective route with the sequence of waypoints crossed.

5.2.2.4 Staging Tables:

These tables act as temporary data repositories for the data to be used by the FPST Tool. These tables are only filled when the application is running since it requires the inputs from the user to select the filtered data. The tables mentioned are the following:

- **Routes_Per_Row_M1(M3):** These tables will store all the information about the flights that comply with the inputs, such as the initial and final points, which can be airports or waypoints.
- **RouteStatistics_M1(M3):** These tables are a simplification from the tables above since they only contain the flights grouped by similar routes that will be available in the output files generated by the Tool.
- **Affected_Sectors:** This table is only filled after having all information gathered, which allows determining which regulations affected the selected flights and which sectors were affected by them.

5.2.3 Stored Procedures

Now that all files to export and tables necessary to be created in order to store that data are described, comes the process in which the data itself is stored into the tables and manipulated afterwards. In order to automate these processes, becomes necessary to create some "Stored Procedures". Stored Procedures are pieces of code that, when used multiple times, can be stored and then is just necessary to call and execute them [25].

Therefore, multiple Stored Procedures were created to simplify the process of importing data and its manipulation, such as:

5.2.3.1 Importing Process

Whenever new files become necessary to upload to the database, either to update the current data or to insert new types of data, the following procedures shall be run:

- **BulkInsert_Geo:** This procedure is used to automate the data uploading into the next tables:
 - dbo.AIRPORTS;
 - dbo.MAP_DEG;
 - dbo.NAV_POINTS.
- **BulkInsert_Charges:** Similar to the previous procedure, this one imports the following files, taking into consideration their extension:
 - dbo.CRCO_UnitRates;
 - dbo.CRCO_AircraftWeights.
- **spBulkInsert_M1(M3):** These procedures are used to insert the data from the "Initial.so6" and "Actual.so6" files into the database. It uploads all files that contain these segments of the name. When the database is not empty, it checks which days of data are already uploaded and only updates with data from more recent days, preventing the repetition of information. Also, after importing that data into the "SO6_M1(M3)" tables, it also applies at the same time the pre-determined filters into the data and inserts it into the "SO6_FILTERED.M1(M3)" and "FROUTE.M1(M3)" tables.

5.2.3.2 Route Statistics

Regarding the routes themselves, it is still necessary to create procedures that, after having the selected flights that, in fact, cross the selected waypoints or have the origin/destination airports matching the inputs from the user, performs the necessary manipulation in order to obtain the desired results. Therefore, the following procedures were created:

- **RouteInfo.M1(M3)**: These procedures are the most complex ones in this project, being them that perform most of the data manipulation in order to obtain the intended results.

This procedure has numerous tasks, such:

- It is divided into four cases, that correspond to the cases in which the user chooses "Airport-Airport", "Waypoint-Airport", "Airport-Waypoint" or "Waypoint-Waypoint";
- It also sums the length of each recorded segment for every flight, giving the total route length;
- Checks if any flight suffered the effects of a regulation delay and if yes, finds which regulation was and records the total of delay incurred, the sector or airport affected and the reason for the regulation to be applied;
- Fills the "Affected.Sectors" table with the information about which sectors were targeted with a regulation and therefore induced delays to the crossing flights.

- **RouteInfo.M1(M3)_1(3)**: Follows the same principle as the previous procedures, but these are called when the user chooses, as input, the option "Middle Point". These procedures will have the additional task of choosing only the routes that cross the three chosen points and after that apply the same queries to the data.

Also, when all data manipulation inside the database is complete, the procedures write the average values grouped by similar routes and inserts them in the table named "RouteStatistics.M1(M3)" which in the end will be the one read by the program to write the values in the output files, as will be seen in the following sections.

5.3 Graphic User interface

Now that most of the data was already treated, its time to start the development of the application itself.

For a better understanding of how the application is structured, it was assumed that starting with the inputs would facilitate its comprehension. Therefore, in this section, the developed Graphic User Interface (GUI) will be presented before how the application was built.

5.3.1 Main Window

In order to turn the application more user-friendly, a GUI was developed. When the user starts the application, the following "Welcome Window" appears:

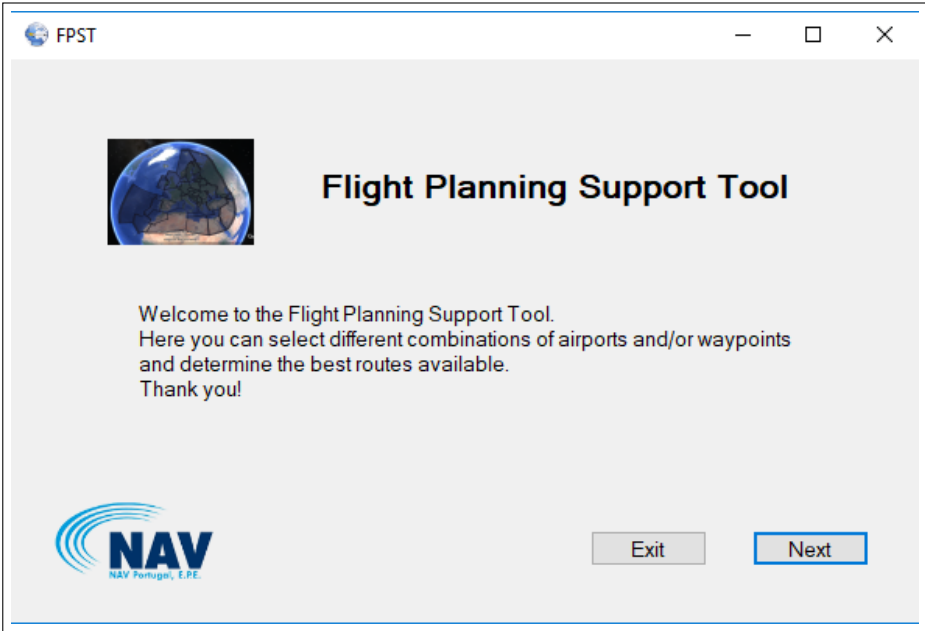


Figure 5.2: Welcome Window.

After this initial window, the user can proceed to the Main Window. In this, the user is free to choose what to analyse. There are five options that can be selected, four dedicated to analysing pre-existent routes, which are "Airport-Airport", "Waypoint-Airport", "Airport-Waypoint" or "Waypoint-Waypoint". In case the user wants to test a new route, in which he may be able to choose the waypoints he wants, there is the option "Test New Route", as can be seen in the Figure 5.3:

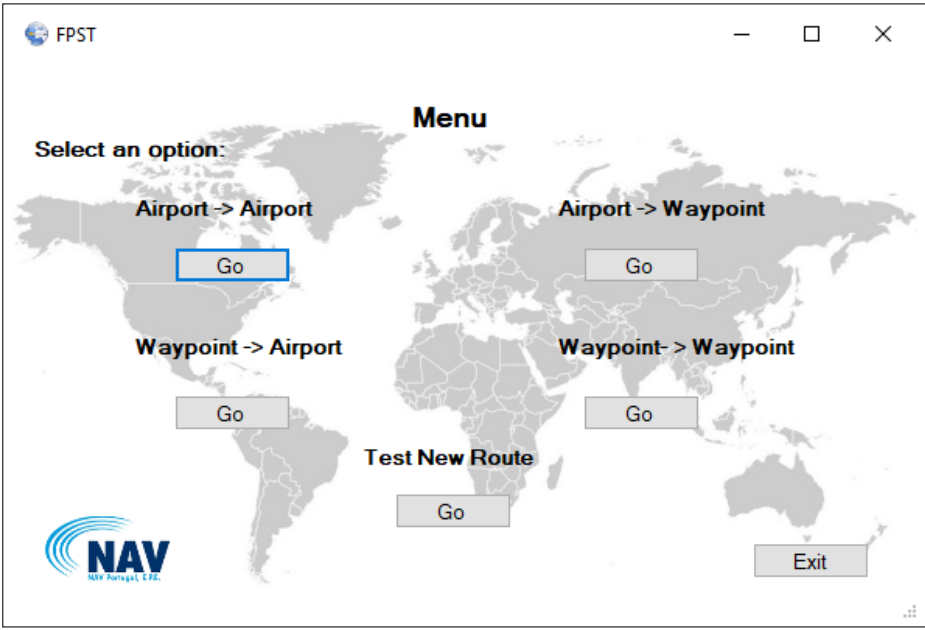


Figure 5.3: Graphic User Interface's main window.

When in this window, the first recommended step is to choose one of the upper four options, since it is assumed that initially, the user wants to find which are the routes more often used by airlines and their respective statistics, such as route length, associated average delay, cost or waypoints crossed along the route, in order to choose the best one. When selecting one of these options, a window, similar to the Figure 5.4, will pop-up:

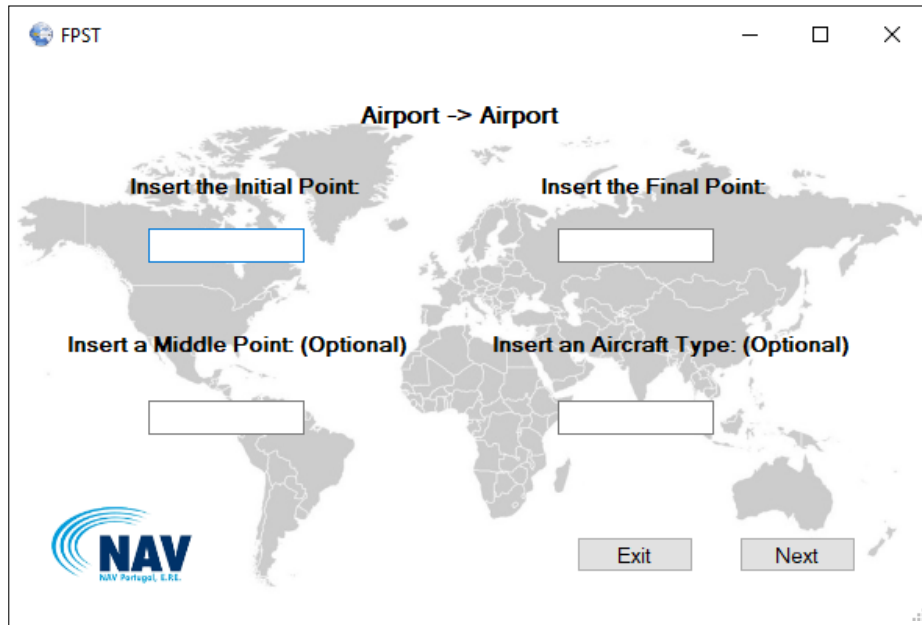


Figure 5.4: Window with the option to select the initial and final route points.

The figure above shows where the user inserts the inputs necessary to run the program. The critical inputs are the initial and final points, which will determine the routes and respective flights that will be selected by the application. Also, in case the user wants to find routes that cross two waypoints or airports, but also pass by an intermediate point, he can add the name of that waypoint in the "Insert a Middle Point" box. As well, he can choose the type of aircraft desired. This last option won't influence the routes chosen by the program, it will only affect the calculated CRCO Costs since, as it was seen in the section 2.2.2, the Aircraft Type is one of the necessary parameters in the CRCO Charges formula.

The last two mentioned options are non-mandatory which means that, if no middle point is inserted, the program will only choose the routes that cross the initial and final points and in case no Aircraft Type is also inserted, the program will assume a Weight Factor of 1.

In case the user wants to check how a new route would behave, he can select the "Test New Route" option. As mentioned, this option is recommended to be selected after the aforementioned analyses are made, since it is where he can choose one of the existent routes and change some waypoints if desired. The window that opens is as follows:

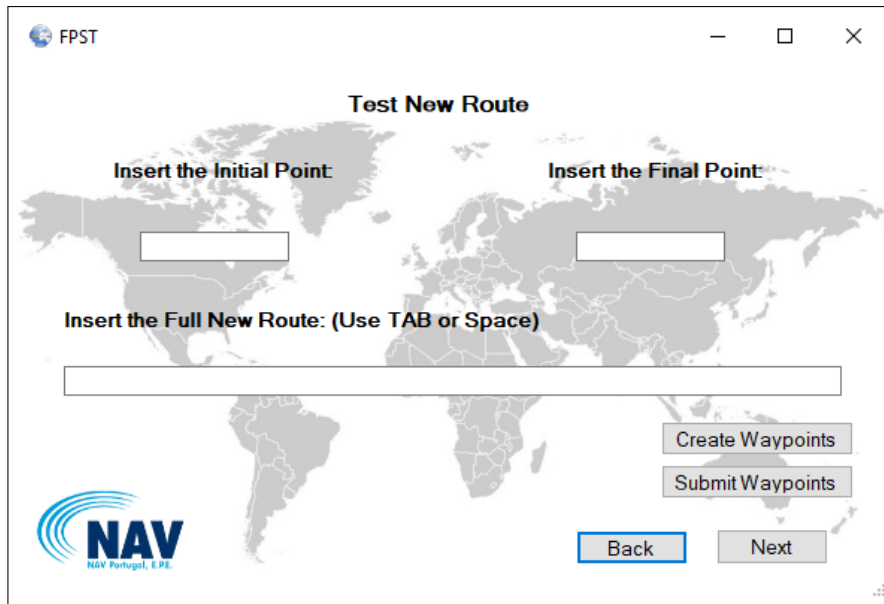


Figure 5.5: New Route Window.

In this window, the user can choose the desired route. He is still required to fill the initial and final points of the route in test. In the bar, the user can insert the sequence of waypoints of the new route. It was designed in order to be user-friendly, which means that assuming the user previously performed the test with the existing routes, he will be able to copy a route and simply paste it in the bar and then edit it as he wants, such as delete waypoints and insert new ones.

In case it is intended to test how a new, non-existent waypoint would affect a route's performance, it can be created in the "Create Waypoint" button, present in the right lower side of the window. When pressed, the following window appears:

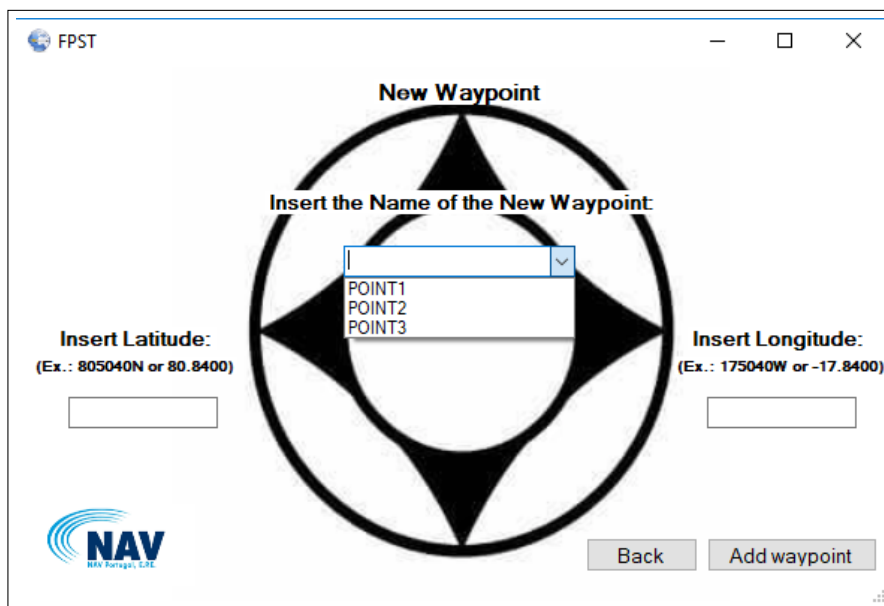
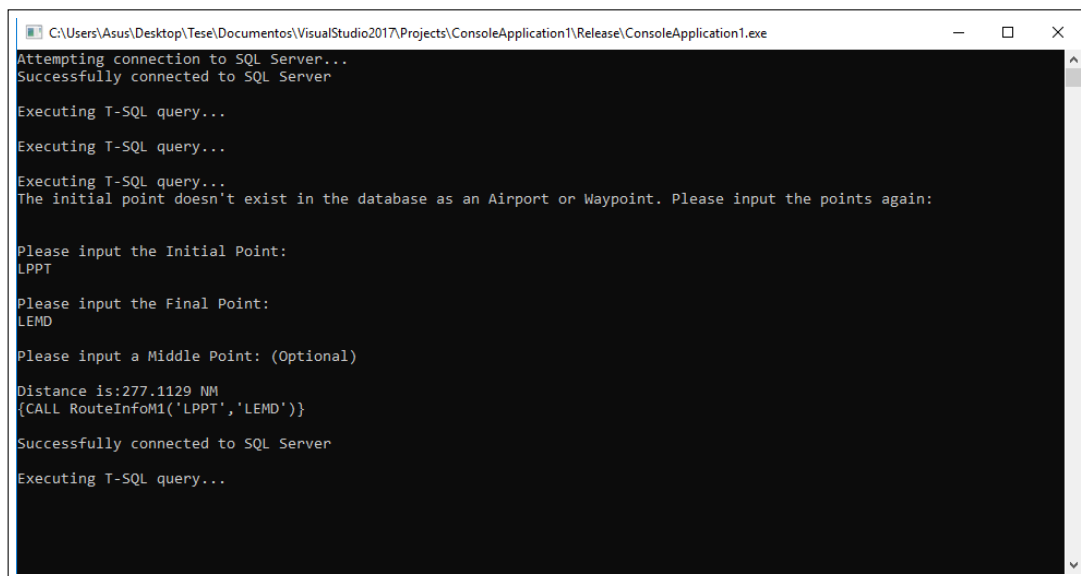


Figure 5.6: New Waypoint Window.

Here, it is possible to create new waypoints. To do that, the user chooses an available name and inserts the coordinates, in the respective boxes. After pressing the "Add Waypoint" button, the introduced waypoint will be added to the cache. Whenever the user wants to stop adding new waypoints, he must press the "Submit Waypoints", shown in figure 5.5, the waypoints will be added to the database and ready to be used by the program. When the insertion process is complete, this window closes and the program returns to the "Test New Route" Window, in which the user can introduce the created waypoint in the new route.

If any mistake is done by the user, such as the insertion of non-existent waypoints or airports or misspelled names, the program runs, opening the console, but a warning is shown and new initial points are required to be introduced again, but this time directly in the console window, as shown below:



```
C:\Users\Asus\Desktop\Tese\Documents\VisualStudio2017\Projects\ConsoleApplication1\Release\ConsoleApplication1.exe
Attempting connection to SQL Server...
Successfully connected to SQL Server

Executing T-SQL query...
Executing T-SQL query...
Executing T-SQL query...
The initial point doesn't exist in the database as an Airport or Waypoint. Please input the points again:

Please input the Initial Point:
LPPT
Please input the Final Point:
LEMD
Please input a Middle Point: (Optional)

Distance is:277.1129 NM
{CALL RouteInfoM1('LPPT','LEMD')}
Successfully connected to SQL Server
Executing T-SQL query...
```

Figure 5.7: Error message and new inputs request.

5.4 SQL Connection

Once the "Next" button, as seen in figure 5.5, is pressed, the inputs are collected and stored in auxiliary excel files that will later be read by the application. In this step of the process a window similar to the one in the figure 5.7 will show up, this time without the error message and the program will do its work. The aforementioned stored procedures such as RouteInfo.M1(M3) will be called by the program which will proceed with the data manipulation.

The first step once the program is running is to attempt the connection to the SQL Server Database. After successfully connect, the application will retrieve information from the tables and insert it into vectors, in order to be used in the C++ application. For each table, the different columns are stored in different vectors that can be connected by a structure to facilitate the data organization inside the c++

environment. All information necessary to upload to the database, that was mentioned in the previous chapter, such as Airport ICAO Codes and Navigation Points will now be essential for the program to compare with the inputs from the user in order to check if those inputs match existent airports/waypoints and if yes, search for the intended flights.

If every input matches with existent airports or waypoints in the database, previously imported to the program and stored as vectors and there are flights in the database that also match those inputs, the coordinates of the limit points of the route are obtained and by applying the Haversine Formula, the length of the orthodromic line that crosses the two introduced points is calculated. In order to provide an immediate perception to the user, that value (the smallest length possible between the input points) is presented immediately in the console. Also, at the same time, the application calls the stored procedures "RouteInfo_M1" to proceed with the analysis of the planned routes and after that calls the stored procedure "RouteInfo_M3" which will analyse the real routes flown. If the user provides three points as inputs, the procedures called will be, as previously mentioned, the "RouteInfo_M1(M3)_1(3)".

```
Distance is:277.1129 NM
{CALL RouteInfoM1('LPPT','LEMD')}

Successfully connected to SQL Server

Executing T-SQL query...
```

Figure 5.8: Initial info presented to the user.

Once the procedures are executed and the auxiliary tables are filled, the program checks if they are empty or not. In case they are empty, that means that there are no routes between the select points in the database and in that case the user gets the opportunity to insert new initial and final points. After this initial step is complete and the tables and vectors are filled, the program starts to do the real work, by calculating the route's costs, distances, delays and so on. The program will divide the data into three modules:

- Orthodromic Route;
- Planned Routes;
- Real Routes.

5.4.1 Orthodromic Route

The first step when all the inputs are correctly defined is to determine the characteristics of the most direct route, which is the orthodromic line between the points defined. This route will have the lower length and has the objective to act as a comparative route for the planned and real ones. Also, it will

have an associated cost, which, although corresponds to the smallest length may not have the smallest cost, due to the different Unit Rates in each airspace.

But, since from the database the program only gets the coordinates of the points, it is necessary to determine which airspaces the route crosses and the length of the segments in each airspace. In order to do so, the program runs the following algorithm composed of 3 main loops:

- A loop that, using the algorithm described in section 3.3 detects if the route crosses any sequence of two points that define each FIR;
- A loop that tries to identify what is the initial FIR and, afterwards, sort the intersected FIRS since in each intersection point correspond two different FIRs;
- A loop that after having the correct sequence of intersected FIRs, find the corresponding Unit Rates and determine the total route cost.

To show how the routes are viewed by the program, in the figure below there is a representation in Google Earth of a random route:

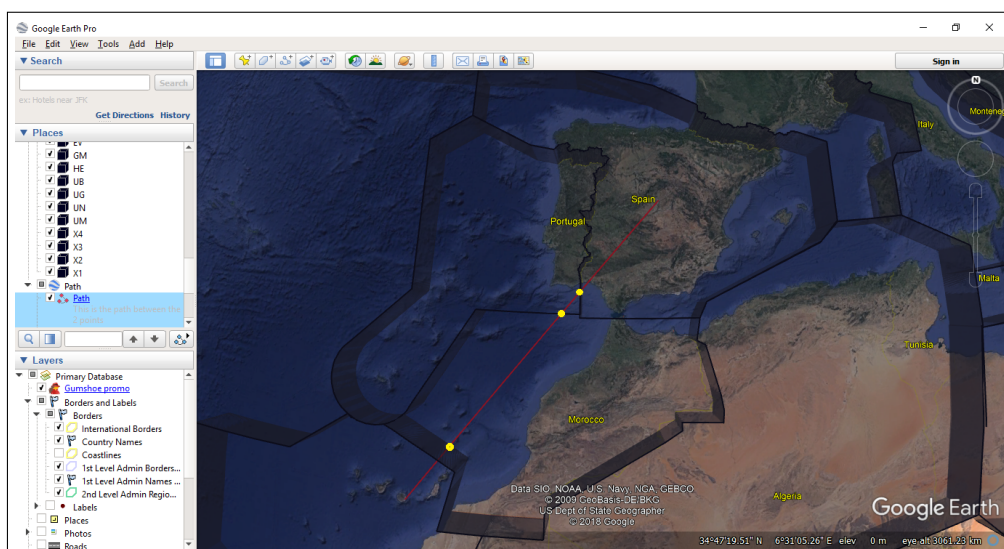


Figure 5.9: Example of orthodromic route and intersections with FIR's borders (GCLP-LEMD).

In order to better understand what is the function of each loop in the algorithm, a detailed explanation will be done below:

Loop 1: This initial loop has the objective of finding the intersection points with each FIR. It starts by getting all the coordinates of the points that define the FIR's borders (given by the ".are" file). Then, since in this section there is only one segment in analysis (segment between the initial and final points introduced by the user), it is only necessary to check the intersections once. To do that, the code goes through all the points contained in the file that describe all borders and checks, using the algorithm described in section 3.3, if at any instance, the route segment intersects any two consecutive border points. Every time an intersection is detected, the distance between the intersection point and the segment's

initial point is calculated and stored in a vector. It is also important to note that there are always two pairs of points that correspond to the same intersection point, since one belongs to the FIR where the segment was already in and the other to the FIR that the segment is entering, which after will lead to another loop to be done in order to detect what was the incoming FIR and the leaving FIR.

```
1: procedure INTERSECTION POINTS
2:
3:   for (i=0; i < No of points that create FIRs; i++)
4:     do Perform algorithm to check if there is intersection
5:       if Yes
6:         then Save lat, lon, fir name, dist.
7:       if Not
8:         then Check next two points.
      sort (Stored vector, by ascending distance)
```

Loop 2: The second loop has the objective of, as was seen, organizing the intersection points of each route and remove the ones that are duplicated, storing them in a new vector by the correct sequence. To do that, the algorithm initially has to determine which is the initial FIR. If the initial point corresponds to an airport, then it can automatically determine the initial FIR, by checking the first two letters of the airport's ICAO code. But when the initial point is a waypoint, then the process to determine to which charging area it belongs is not so trivial, since the program doesn't have access to any file that relates the waypoints to their respective FIR.

The detection of in which FIR is the waypoint, is done by checking the following intersection points. Initially, it checks the first intersection point, that gives two FIRs, it starts by assuming that one of them is the initial FIR. Then, it means that the other one is the FIR where the segment is entering. Therefore, the second intersection point has also two corresponding FIRs, which one of them has to be the leaving FIR. If any of these two FIRs is equal to the FIR that was assumed by the second FIR, then the initial guess is correct, if not, it means that it was incorrect and therefore the initial FIR is the one that was not chosen initially. If the route leaves the initial FIR and then returns to that FIR, the program has to do this analysis until find an error meaning that the initial FIR that was chosen is not the correct.

```
1: procedure ORGANIZE BY CORRECT SEQUENCE
2:
3:   if Initial Point = Airport
4:     then Check first two letters of icao code
5:       Compare with the first two stored points
6:       Determine which corresponds to the first FIR.
     Else Check next two points.
```

Loop 3: After having the correct sequence of FIRs crossed and the respective length of the route inside each FIR, it is necessary to calculate the total length and the cost of that route. To do that, first is necessary to run a loop that will find the Unit Rates of each crossed FIR. It will access the database and store into a struct type vector the information from the "CRCO_UnitRates" file and then within the loop, each FIR crossed by the route will be compared to the ones inside that previous vector and when matched, the Unit Rates will be taken. Then, each unit rate is multiplied by the length crossed in each charging area. Then, a sum of all segment costs and the total length is stored and later displayed in the output files.

```

1: procedure INTERSECTION POINTS
2:
3:   for (i=0; i < No of points that create FIRs; i++)
4:     do Perform algorithm to check if there is intersection
5:       if Yes
6:         then Save lat, lon, fir name, dist.
7:       if Not
8:         then Check next two points.
          sort(Stored vector, by ascending distance)

```

5.4.2 Planned and Real Routes

Regarding the Planned and Real Routes, the biggest challenge is that contrary to the Orthodromic Route, these have multiple segments formed by the different waypoints, while in the Orthodromic Route there is only one segment. So, there are more cases to take into consideration such as if the segment intersects or not FIR's borders and if not, the program has to save the distance of that segment.

To do that, another loop is added to the algorithm that does exactly that, checks segment by segment if there is any intersection. However, some special cases must be taken into consideration such as, when dealing with initial points that ain't airports/aerodromes, it is necessary to determine the initial and final FIR, requiring an extra loop to be run. Also, in the middle segments and as was said previously, whenever a segment doesn't leave any charging area, there are no intersections and the distance of that segment needs to be computed with the "Haversine Formula" and stored in order to be added to the other segments that are within the same charging area, giving, in the end, the total length of the route inside the FIR.

5.5 Output Files

Now that all information is analysed and all calculations are performed is necessary to export them in order to be available for the user to see the results and use the information created. In order to do so, the program will produce two different output files, an excel file and a ".kml" file (google earth). The information contained in each will be detailed below:

5.5.1 Excel

In order to display the results of the program, it was chosen Excel since it is a widely used and very intuitive spreadsheet. It is structured in three different spreadsheets in order to facilitate the data organization, which are the "Orthodromic", "Planned Routes" and "Real Routes".

5.5.1.1 "Orthodromic" Sheet

This initial sheet contains a header with the input information, such as the initial and final points, the weight factor correspondent to the aircraft considered (in case the user doesn't select an aircraft type, the considered weight factor will be 1) and the date of the most recent file contained in the database and therefore analysed by the program.

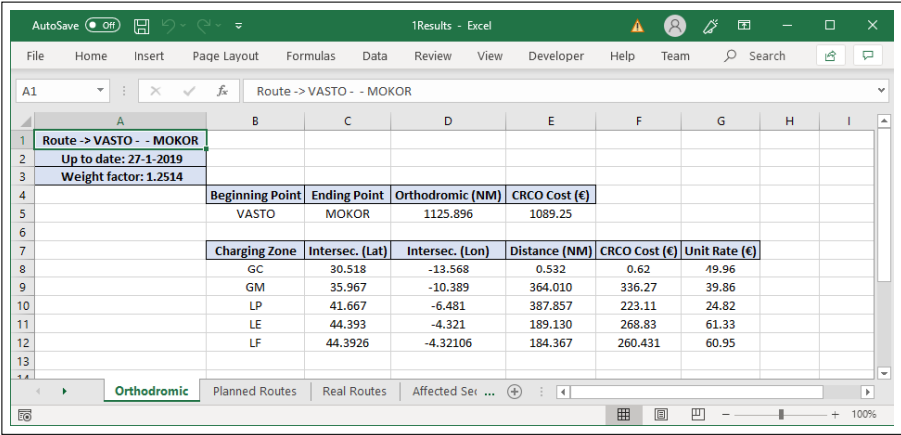


Figure 5.10: Example of the "Orthodromic" Sheet in the output excel.

In this sheet is also displayed the information about the orthodromic arc formed by the input points. It is given the distance between them and the CRCO Cost that a route like that would have. The data in this sheet acts more as a comparative information for the following sheets such that the user can compare the values of the planned and real routes with what would the distances and CRCO costs be like if the plane had flown the most direct route. Below that, the charging zones crossed are discriminated in order to allow a better comprehension of the route itself. It is presented, by order of crossing, the charging zones crossed, the length of the route inside that charging zone, the respective Unit Rate and

the coordinates at which the path exits the FIR's border, except for the last charging area, which the intersection point respects to the entering point since it doesn't have an exit point.

5.5.1.2 "Planned Routes" Sheet

The second excel sheet contains information about the Planned Routes. These are the routes that were submitted in the flight plans before the actual flights. The routes selected in the flight plans are the ones that will decide the cost of the flight even though during the flight itself, the pilots or ATC decide to change the route, so these are the most important routes to analyse.

Since the objective of this program is to create a compilation of information, in this section, all the routes that have the same sequence of waypoints are grouped and the information related to them is presented as an average. Therefore in the following bullet points, a description of the information in each column will be given:

	Nº Flights	Calc. Length (NM)	Length Diff. (NM)	Percentage (%)	T. Delay (min)	Avg. Delay (min)	Most Affected Sector	CRCO Cost (€)	CRCO Cost Diff. (€)	Fuel Burn (Kg)	Est. CO2 (Kg)	Route
4	212	1130.790	4.899	0.44	365	1	MASBSWL; LPSOUTH1; LPCEU1	1148.70	59.45	7194.04	22661.20	VASTO SUL
5	202	1129.670	3.771	0.33	512	2	LPSOUTH1; LPCEU1; LFTOPON	1175.13	85.89	7187.82	22641.60	VASTO SUL
6	165	1129.300	3.399	0.3	276	1	LPSOUTH1; LPCEU1; LFRNORD	1202.36	113.11	7185.77	22635.20	VASTO SUL
7	75	1133.790	7.897	0.7	236	3	MASBSWL; LPSOUTH1; LPCEU1	1231.48	142.23	7210.58	22713.30	VASTO SUL
8	73	1130.820	4.925	0.44	232	3	LPSOUTH1; LPCEU1; LFEHYR	1148.70	59.45	7194.19	22661.70	VASTO SUL
9	71	1130.790	4.899	0.44	182	2	LPSOUTH1; LPCEU1; LFRNU	1148.70	59.45	7194.04	22661.20	VASTO SUL
10	70	1133.610	7.713	0.69	109	1	LPSOUTH1; LPCEU1; LFEHYR	1231.02	141.78	7209.57	22710.10	VASTO SUL
11	69	1129.350	3.454	0.31	147	2	MASBWST; LPCEU1; LFEFR	1210.36	121.11	7186.07	22636.10	VASTO SUL
12	67	1145.140	19.240	1.71	110	1	MASBWST; LPCEU1; LFEUBN	1110.03	20.78	7273.15	22910.40	VASTO SUL
13	67	1129.300	3.399	0.3	99	1	LPSOUTH1; LPCEU1; LFRNU	1202.34	113.09	7185.77	22635.20	VASTO SUL

Figure 5.11: Example of the "Planned Routes" Sheet in the output excel.

- In the first column, **Nº of Flights**, is presented the number of flights that indeed have the same path as route during the interval of time of the files uploaded to the database. The routes are ordered by this parameter, being the most used routes the ones that are shown.
- In the second column, **Calculated Length**, is presented the total distance flown in that specific route. If the initial points belong to airports, the length presented will correspond to the total route, if the points chosen are waypoints, then the length presented will only correspond to the length of the segments between those waypoints, which will be different from the respective full routes.
- In the third column, **Length Difference**, is shown the difference in Nautical Miles of the average route length with the orthodromic route length. This column acts as a comparative method to better detect which are the shortest routes, while in the fourth, **Percentage**, this difference is converted to allow an easier and faster detection of the smaller/longer routes.
- In the fifth column is the **Total Delay** caused by regulations. This is the delay that all flights with the same route suffered due to regulations applied when there are constraints in airports or airspace.

- Meanwhile in the fifth column is the **Average Regulation Delay** which is the average delay per route, to allow to prevent outlier results that could increase by a lot the delay and lead to misinterpretation of the results.
- In the seventh column are the **Most Affected Sectors** in which are the top 3 sectors that lead to highest delay times organized by descending order.
- In the eighth column are the **CRCO Costs** that are also one of the most important aspects to help in the determination of the best routes, since getting the routes with the less associated costs is the objective of all parties and in the ninth column is the difference with respect to the CRCO Cost of the Orthodromic Route.
- Regarding the tenth and eleventh columns, are presented the **Fuel Burn** and the **Estimated CO₂** emitted. This is a very interesting parameter to estimate since nowadays the environmental impact of aviation is being subjected to more attention and achieve routes that are less pollutant is a very important subject.
- In the last column, **Route**, is the sequence of waypoints which constitute the respective routes.

5.5.1.3 "Real Routes" Sheet

In this sheet is contained the information about the Real Routes that were actually flown. Similarly to the "Planned Routes" Sheet, the type of information that is presented is almost the same.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		Real-Top 10															
2		Nº Flights	Calc. Length (NM)	Avg. Full Length (NM)	Length Diff. (NM)	CRCO Cost (€)	CRCO Cost Diff. (€)	Route									
3		18	1145.140	1144.370	18.477	1110.03	20.78	VASTO SULAM BAROK BALNO LOTEE NOVAN ERIGA MOKOR									
4		16	1143.370	1142.600	16.706	1110.03	20.78	VASTO SULAM BAROK BALNO LOTEE NOVAN ERIGA MOKOR									
5		11	1143.370	1142.600	16.707	1110.03	20.78	VASTO SULAM BAROK MAGUM BALNO LOTEE NOVAN ERIGA MOKOR									
6		5	1153.310	1152.810	26.913	1132.10	42.85	VASTO SULAM BAROK PINEK LOTEE NOVAN ERIGA MOKOR									
7		4	1145.140	1144.370	18.478	1110.03	20.78	VASTO SULAM BAROK MAGUM BALNO LOTEE NOVAN ERIGA MOKOR									
8		4	1143.470	1142.700	16.803	1110.03	20.78	VASTO SULAM BAROK TROIA BALNO LOTEE NOVAN ERIGA MOKOR									
9		3	1143.430	1142.660	16.761	1110.03	20.78	VASTO SULAM BAROK ATECA MAGUM BALNO LOTEE NOVAN ERIGA MOKOR									
10		3	1145.160	1144.400	18.501	1110.03	20.78	VASTO SULAM BAROK ATECA BALNO LOTEE NOVAN ERIGA MOKOR									
11		3	1133.260	1138.450	12.552	1089.83	0.58	VASTO SULAM BAROK BALNO GATMO ERIGA MOKOR									
12		2	1143.860	1143.090	17.197	1110.02	20.78	VASTO SULAM BAROK ADSAD BALNO LOTEE NOVAN ERIGA MOKOR									
13																	
14																	

Figure 5.12: Example of the "Real Routes" Sheet in the output excel.

It is relevant to note that in this section, the delays induced by regulations are not computed since they are the same for the planned and real routes. There is not a straight relation between the real routes and the delays. Therefore and for the sake of this thesis, the delays will be considered as a statistic parameter related to the planned routes as done in NEST.

5.5.1.4 "Affected Sectors" Sheet

In this last sheet, the objective is to detail the most affected sectors crossed by the selected flights, in order to determine which sectors shall be avoided to decrease the overall delay. A cross check is done by the tool such that only the sectors crossed are selected and therefore reduce the non-necessary information presented.

After the program determine the sectors that were subjected to regulations and the previous mentioned stored procedures in SQL are run, the results are presented as follows:

	Sectors Affected					
	Total Delay	Nº Flights Affected	Avg. per Flight	Nº Days Affected	Sector Affected	Reason
3	2837	358	7	4	LPCEU1	ATC CAPACITY
4	1919	127	15	4	GCCCRNE	ATC CAPACITY
5	720	49	14	10	LPMAD1	EQUIPMENT ATC
6	408	24	17	1	ESSAARR	WEATHER
7	207	18	11	1	LPSOUTH1	MILITARY ACTIVITY
8	197	26	7	2	LECMZMUX	ATC CAPACITY
9	133	26	5	1	LPSOUTH1	ATC CAPACITY
10	78	8	9	2	EDDHARR	ATC STAFFING
11	77	6	12	3	EDUOH	ATC STAFFING
12	74	19	3	7	LFEHYR	ATC CAPACITY
13	71	6	11	1	LFRG	ATC STAFFING
14	68	6	11	1	EDGG1	ATC STAFFING
15	64	4	16	1	EDWWSUD1	MILITARY ACTIVITY
16	52	4	13	1	EDUFFM1F	ATC STAFFING
17	52	16	3	9	LFE4N	ATC CAPACITY
18	52	34	1	9	LFESR	ATC CAPACITY

Figure 5.13: Example of the "Affected Sectors" Sheet in the output excel.

In this sheet, the information is organized from the most affected sector, in terms of total time of delay, to the least affected one, as follows:

- In the first column, **Total Delay**, is presented the sum of delay that airplanes that crossed that specific sector were subjected to;
- Then, it is shown how many aircraft were indeed affected when crossing that sector. This is a relevant detail since if there is a sector very affected and also a huge number of flights crossing that sector, is an indicator that those routes shall be redesigned in order to prevent large delays;
- Then, in the **Nº of Days Affected** is intended to be shown the number of days that each sector was affected by regulations. If a sector has a large delay associated, but the number of days that it was affected by regulations is low, then it means that perhaps it was just an occasional situation and therefore, usually it is a good sector to fly through.
- In the last columns, are represented the sectors subjected to the regulations and the main reasons for their associated delay.

5.6 Google Earth

Another output file produced by the program is two ".kml" files, which can be open in Google Earth. One of the files is named "FIRS" and contains the data necessary to draw the airspaces in Google Earth allowing the user to have a better perception of which airspaces are crossed by the routes and where are the intersections.

The other file created is named "Trajectories" and contains:

- The Orthodromic line between the initial points represented as a red line;
- The Planned Flights, represented as a green line; The different routes are organized by descending order of frequency of flights, matching the order they are presented in the excel file;
- The Real Flights, represented as blue lines and they are also presented by descending order of frequency.

When the "Trajectory" file is opened, all routes are already pre-selected, but the user has the possibility to select and deselect the routes he wants in order to have a better visualization of the intended ones for comparison.

An example of how the routes are shown in Google Earth and where the user can select and deselect them is presented in the figure below. As well, it is possible to see that every route is tagged whether they are planned, real or the orthodromic routes and numbered by descending order of most common routes.



Figure 5.14: Example of how routes are presented in Google Earth (VASTO-MOKOR).

In order for the user to select which routes are displayed or which FIRs are represented, there is a panel on the left side of the window with all available FIRs and a second panel with the routes selected by tool. These panels are represented below:

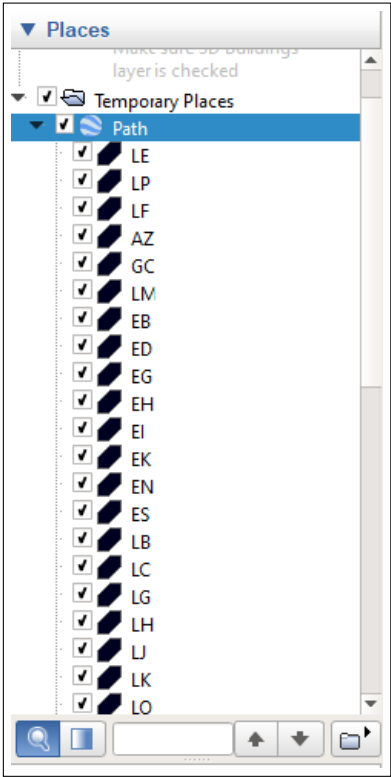


Figure 5.15: Selection of FIRs.

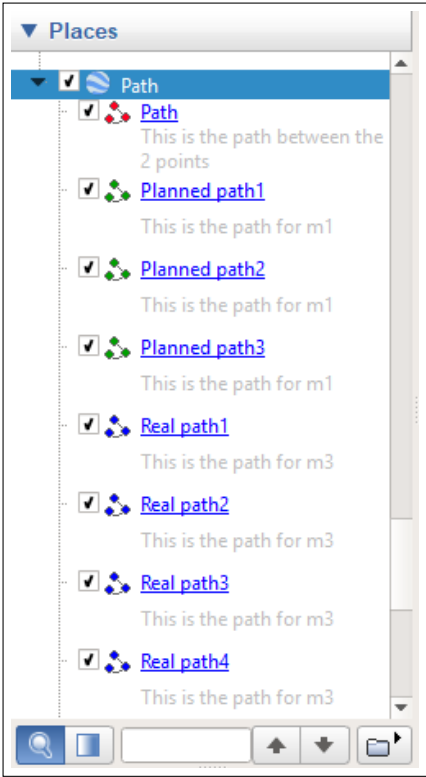


Figure 5.16: Selection of routes.

With these options and especially when the user wants to test a new route, he can select only that specific route or others that he may consider relevant to compare with, and see in detail which FIRs are crossed, where are they crossed or even measure the distance flown by a specific route in a specific FIR.

This option is very relevant in this tool since when the user doesn't have much experience and knowledge of the most common waypoints, it may be hard to understand how the routes are designed. On another hand, having this visual capability, even those users can retrieve useful information from this tool and use it to design better routes.

Chapter 6

Results

In this section, different studies are conducted regarding the efficiency of routes and the design of new and more efficient ones. Before, some validation tests will be conducted to verify if the results are correct and as close as possible to the reality.

6.1 Results Validation

Before performing detailed studies with the developed tool, it is necessary to determine if the results are correct, or at least, as close to the real values as possible. To do so, two different cases will be studied and the values obtained from the program will be compared with the ones obtained from the program "NEST" using the methods explained in subsection 4.3.

6.1.1 EGLL-LEMD Route

To start the verification of the results, one specific flight was selected among the thousands of flights that fly over the Eurocontrol Member States. So, the flight "AA10085295" was chosen with the following Flight Information:

Table 6.1: Flight Information about "AA10085295" flight.

Departure:	EGLL	Dep. Time:	17:30
Arrival:	LEMD	Arr. Time:	19:23
CallSign:	IBE3171	Date:	27/01/2019
Airline:	IBE	Aircraft:	A319

In Tables 6.2 and 6.3, a comparison between the values obtained from NEST and the FPST will be shown. It is important to note that since the airplane used to fly this route was an A319, it is necessary to consider a MTOW of 70 that corresponds to a Weight Factor 1.183. The Unit Rates used are the same as the ones that were being used at the time of the flight.

Table 6.2: Comparison between Distances and Costs for the Orthodromic and Planned Route.

		NEST	FPST	Difference (%)
Orthodromic	Distance (NM)	673.03	673.14	0.02%
	CRCO Cost (€)	866.4	866.7	0.04%
Planned Route	Distance (NM)	812.74	813.17	0.05%
	CRCO Cost (€)	935.8	936.3	0.08%

Based on the data shown in Figure 6.2, it is possible to see that when comparing the distances determined by the NEST with the ones determined by the FPST, the difference is very small, having only an error of around 0.05%. Even though this error is small, it can be due to approximation errors resultant from the chosen algorithm or due to the approximations used when converting the coordinates of the points that define the FIR's borders.

When analysing the CRCO Costs, the differences are also negligible.

Table 6.3: Comparison between final route costs for the planned route.

Country	Unit Rate	Length (NM)			Cost (€)		
		NEST	FPST	Difference	NEST	FPST	Difference
EG	58.37	117.44	117.52	0.07%	135.5	135.7	0.13%
LF	60.95	344.83	345.06	0.07%	460.6	460.9	0.07%
LE	61.33	263.43	263.61	0.07%	339.5	339.8	0.07%

In the Table 6.3, it is specified which countries are crossed by the selected route and the respective overflight distances. It is necessary to note that the distances presented are the orthodromic distances between the entering and exiting point of each charging zone. When computing the CRCO Costs, 20km shall be deducted to the charging zones that contain the departure and arrival airports. Knowing how much are the charges for each country it is possible to determine what is the impact of each segment in the overall route cost. Since the charges vary from country to country, it is an important factor to take into consideration when evaluating a route and specially in order to develop new and cheaper routes. Therefore all these factors need to be verified concerning the NEST results.

By evaluating the results presented in the table 6.3, it can be seen that the differences between the results obtained from NEST and the FPST aren't very significant, which means that the algorithm used to perform these calculations is acceptable. However there are some dissimilarities that can be due to the algorithm used in NEST be different than the one used in the FPST. Also, since the points that define the geographic borders of each country, needed to compute the CRCO Costs, were initially wrong as explained previously, when correcting them, perhaps some values were slightly different than the ones considered by NEST, leading to differences in the borders and therefore resulting in different distances for each charging area.

Below, two different images are shown each one representing the selected route. In Figure 6.1, is represented the route designed in NEST and in Figure 6.2 is the resultant from the FPST program. This is also an important information to be confirmed since one of the advantages of the tool is the ability to

present all the main different routes between the chosen airports or waypoints. Also, one advantage in relation to NEST is the capacity of represent any new routes that were created by the user, in order to design new and more efficient routes and compare them with the ones already used.

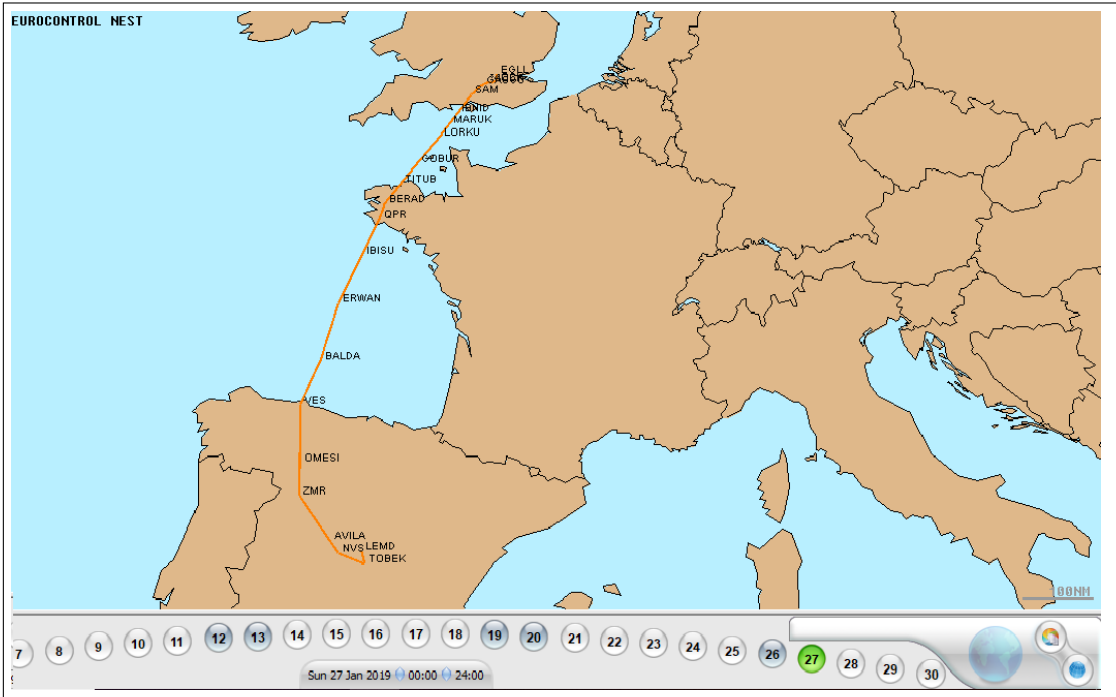


Figure 6.1: EGLL-LEMD Route design in NEST.

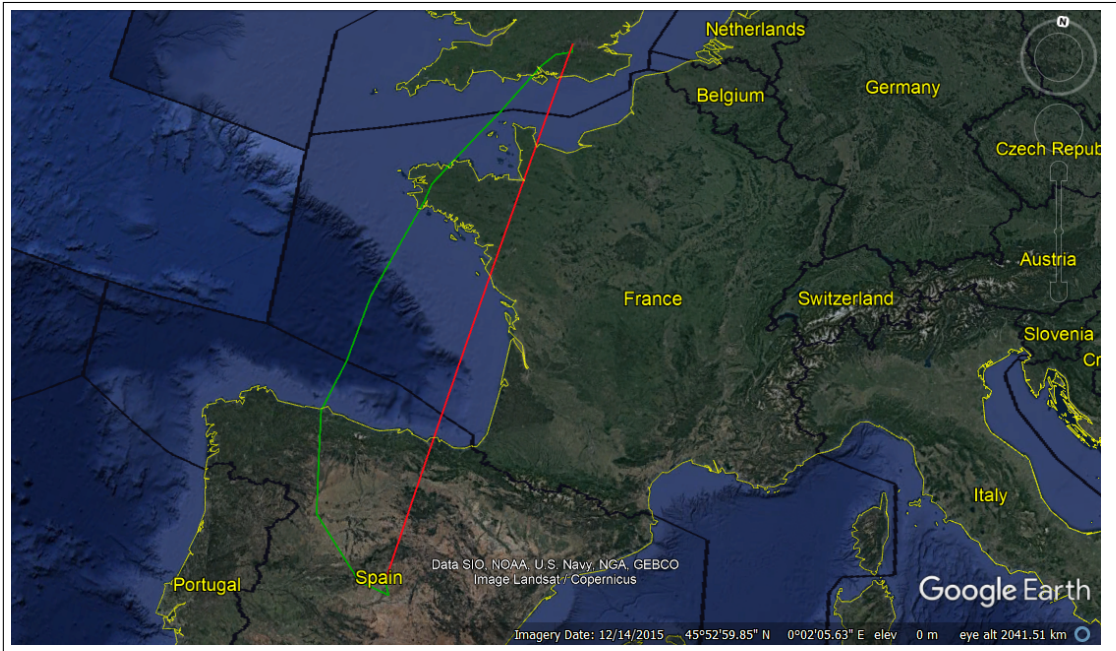


Figure 6.2: EGLL-LEMD Route Design in Google Earth obtained from the FPST.

Note that the red line corresponds to the orthodromic line between the considered airports, while the green line corresponds to the route in study. Comparing both Figures 6.1 and 6.2, it can be verified that they match and therefore the developed tool is working as expected.

6.2 Case Studies

Now that it was proved that the results from the FPST program are correct, they can be used to perform some tests to the current network system. In this section, some routes will be evaluated to what concerns their efficiency, in terms of planned and real routes, taking into consideration distances, costs, sectors crossed and even environmental impact.

Since sometimes the approach area can vary depending on which runway the airplane is cleared to land, besides the Airport-Airport routes, it will also be evaluated cases of Waypoint-Waypoint routes.

Note: All data presented below is resultant from the developed software and belongs to the AIRAC 1901.

6.2.1 VASTO-DGO Route

The first route to be studied in detail is the VASTO-DGO. Consider that it was intended to study a new route for an airline that wants to fly with an A320, whose path must cross the VASTO and DGO waypoints. In this case, and according to the formula 2.2, the Weight Factor is 1.241.

The first step of this study is to determine the information about the orthodromic route between the selected points since this is the shortest and more direct route possible for this case and, therefore, the best way to compare the efficiency of the used routes between those points. Below is the information relative to the orthodromic route:

Table 6.4: General information about the orthodromic route.

Beg. Point	End. Point	Distance (NM)	CRCO Cost (€)
VASTO	DGO	881.9	907.2

Table 6.5: Detailed information about the orthodromic route.

Charge Zone	Intersec. (Lat)	Intersec. (Lon)	Distance (NM)	CRCO Cost (€)	Unit Rate (€)
GC	30.517	-13.567	0.5	0.6	49.96
GM	35.968	-9.195	394.0	360.9	39.86
LP	38.249	-7.141	168.6	96.2	24.82
LE	38.249	-7.141	318.9	449.4	61.33

In table 6.4, a summary of the most important information about the orthodromic route is contained, like its distance and total CRCO Cost. In the table above, 6.5, is presented the necessary information to understand how the total CRCO Cost was computed and what is the influence of each charging zone to the final value. Since the Unit Rate varies from charging zone to charging zone, it is relevant to see which FIRs are the cheapest since flying the same distances in different charging zones can correspond to lower charges and an overall money-saving.

Another important detail is that the Unit Rate for Spain (LE) is almost three times higher than the rate for Portugal (LP). This means that for the same flown distance, the cost is three times lower in the Portuguese airspace. But is also necessary to take into consideration that the longer the distance

flown, the higher the fuel consumption and other expenses. It is then necessary to achieve an efficient proportion. But, in this case, if it becomes possible to find a route with the lowest distance possible and crossing more Portuguese airspace than Spanish, the overall costs are lower. So now becomes important to analyse which routes are more often planned by the airlines and afterwards, which are really flown by them, allowing to determine if are there inefficient planned routes that can be improved.

By running the FPST program, one of the output files contains information about the top 10 most planned routes for each pair of selected points during the AIRAC 1901. This excel sheet details multiple information such as the Length of the planned routes, the respective CRCO Cost based on the length flown in each airspace, the regulations that affected the crossed sectors and the total induced delay to each route. This information related to the case in study is shown in the following tables:

Table 6.6: Top 10 most often planned routes between VASTO-DGO.

Nº	Nº Flights	Length (NM)	Diff. (%)	T. Delay (min)	CRCO Cost (€)	Diff. (€)	Fuel Burn (Kg)	Est. CO ₂ (Kg)
1	149	893.4	1.3	179	969.0	61.9	5811.1	18304.8
2	52	893.4	1.3	162	969.0	61.9	5811.1	18304.8
3	25	901.9	2.3	36	817.2	-89.9	5857.6	18451.6
4	19	901.9	2.3	125	817.2	-89.9	5857.6	18451.6
5	8	901.9	2.3	39	817.2	-89.9	5857.6	18451.6
6	7	900.4	2.1	0	856.8	-50.4	5849.4	18425.7
7	7	893.4	1.3	4	969.0	61.9	5811.1	18304.8
8	5	901.9	2.3	0	817.2	-89.9	5857.6	18451.6
9	4	904.7	2.6	0	877.3	-29.8	5873.1	18500.2
10	3	900.8	2.1	0	838.1	-69.0	5851.5	18432.1

Table 6.7: Waypoint sequence for the top 10 most planned routes.

ROUTE															
1	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	PESAS	OSLEP	OXACA	PARKA	SOLAX	TLD	*SIE	DGO	
2	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	OBOLO	PESAS	OSLEP	OXACA	PARKA	SOLAX	TLD	*SIE	DGO
3	VASTO	SULAM	BAROK	PINOX	TOSDI	ZMR	UNOVI	DGO							
4	VASTO	SULAM	BAROK	OLGAR	PINOX	RIVRO	TOSDI	ZMR	UNOVI	DGO					
5	VASTO	SULAM	BAROK	OLGAR	PINOX	TOSDI	ZMR	UNOVI	DGO						
6	VASTO	SULAM	BAROK	BARDI	ZMR	UNOVI	DGO								
7	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	UBESO	PESAS	OSLEP	OXACA	PARKA	SOLAX	TLD	*SIE	DGO
8	VASTO	SULAM	BAROK	PINOX	RIVRO	TOSDI	ZMR	UNOVI	DGO						
9	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	BARDI	ZMR	UNOVI	DGO					
10	VASTO	SULAM	BAROK	TOSDI	ZMR	UNOVI	DGO								

Analysing the tables above, it is possible to conclude that there are about two/three routes which are widely often selected by airlines. However, looking at the remaining columns of table 6.6, it is possible to verify that the two (2) most frequent routes (checking the table 6.7, it can be seen that they only differ by one waypoint) have a CRCO Cost much higher than the third most used route. It is about 100€ of difference, although the 3rd route is about 8NM longer than the previous. Depending on the extra costs associated with the number of miles flown, this 3rd route can be better or not. But if it is only concerning the CRCO Costs, the 3rd route is the best option.

In the Figure 6.3, the top 10 most planned routes, as shown in the tables above, are presented in Google Earth, as one of the output files generated by the FPST Program. It allows to have a better visualization on how they are distributed and how do they compare to the orthodromic route between the selected points.

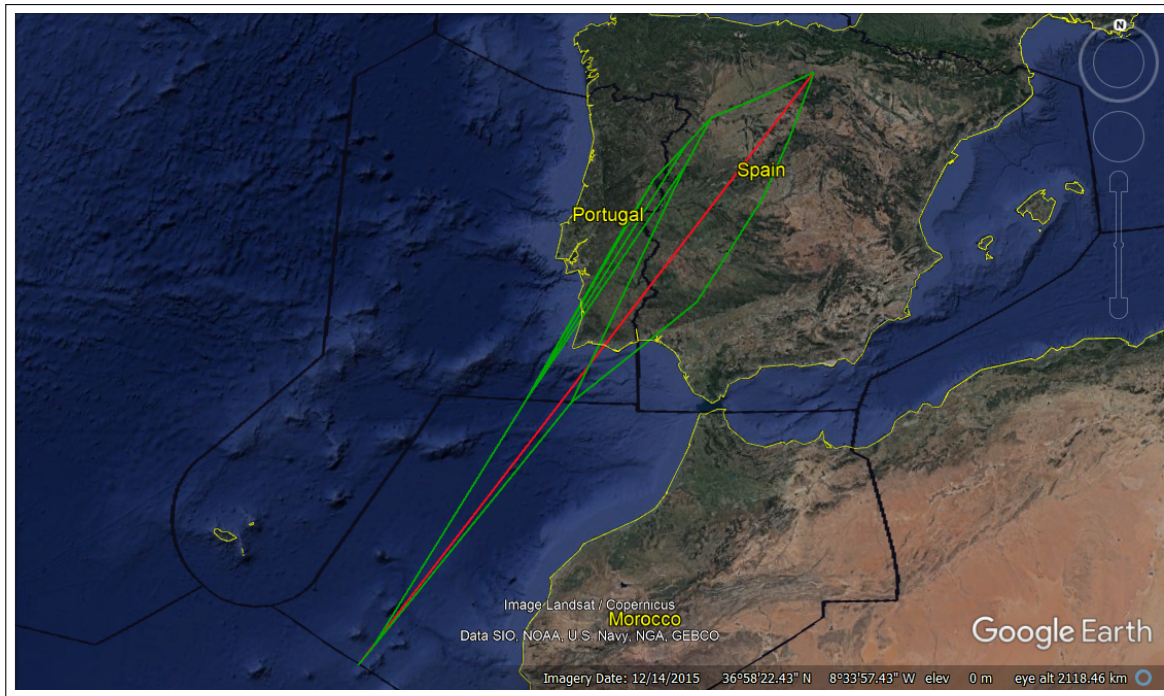


Figure 6.3: Planned Routes between VASTO-DGO.

Looking at the Figure 6.3, it can be seen why some routes are more expensive than others, even though having a smaller length. It is due to the previously referred difference between Unit Rates. Since the shortest routes have a big portion of its length in Spanish Airspace, it will be subjected to higher charges when compared with the routes that have a bigger portion of its length crossing the Portuguese Airspace instead of the Spanish. This is the major difference between the planned routes since, under the Morocco's Airspace, the routes have almost the same length.

Regarding the Delay by Regulation, it can be seen that there ain't much delay in general, having a max average delay of about 6 min, but is already quite significant, because when accumulating these delays over the entire day, it can reflect in hours of delays.

Table 6.8: Top 10 Real Flights between VASTO-DGO.

Nº Route	Nº Flights	Length (NM)	Diff.(%)	CRCO Cost (€)	Diff. (€)
1	37	890.9	1.0	969.0	61.9
2	32	892.8	1.2	969.0	61.9
3	14	890.9	1.0	969.0	61.9
4	13	898.2	1.8	838.1	-69.0
5	8	894.9	1.5	867.7	-39.4
6	8	892.8	1.2	969.0	61.8
7	6	900.2	2.0	838.1	-69.0
8	5	893.3	1.3	856.4	-50.4
9	5	889.8	0.9	972.3	65.1
10	2	891.4	1.2	863.4	-43.8

Table 6.9: Waypoint sequence for the top 10 most flown real routes.

ROUTE															
1	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	DGO		
2	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	PESAS	OSLEP	OXACA	PARKA	SOLAX	TOLD	*SIE	DGO	
3	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	OBOLO	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	DGO	
4	VASTO	SULAM	BAROK	TOSDI	UNOVI	DGO									
5	VASTO	SULAM	BAROK	UNOVI	DGO										
6	VASTO	SULAM	DIMSA	IBLIV	SUNID	AKUDA	OBOLO	PESAS	OSLEP	OXACA	PARKA	SOLAX	TLD	*SIE	DGO
7	VASTO	SULAM	BAROK	TOSDI	ZMR	UNOVI	DGO								
8	VASTO	SULAM	BAROK	BARDI	UNOVI	DGO									
9	VASTO	SULAM	DIMSA	IBLIV	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	DGO				
10	VASTO	SULAM	BAROK	SOTEX	EVURA	PORTA	BARDI	UNOVI	DGO						

Regarding the Real Flown Routes, it can easily be seen (this is one of the advantages of having a graphic characterization of the routes in Google Earth) that there are not many differences between what was planned and what was really flown. In most cases what happens is that, during flight, the pilots or even the ATC tend to ask/allow more direct routes than the ones planned in order to shorten the distance and time, which can be verified by looking at table 6.8 since the length's difference is always around 1%, while in the planned routes, that difference is around 2%.

So, unless there is an active regulation that affects the flight, like bad weather or ATC capacity problems that forces it to deviate its path, the real flown routes tend to be shorter than the planned ones. It can be seen in the figure below since the routes more close to the orthodromic line (red) are the ones belonging to the real flown paths (blue).

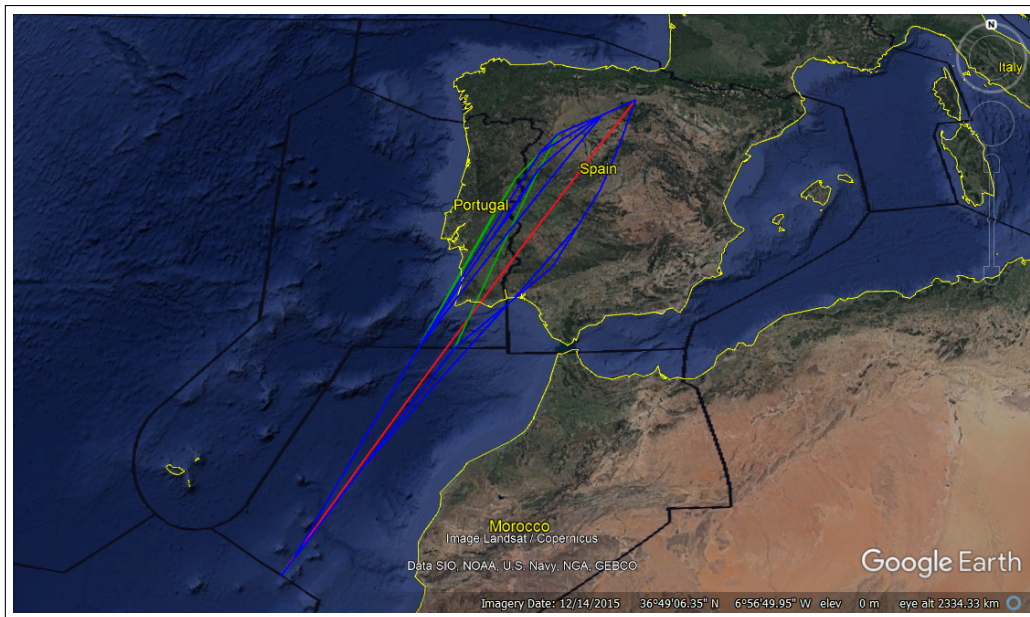


Figure 6.4: Real vs Planned Routes for VASTO-DGO.

When looking at these tables, there is a first step to take which is to see if there any easy possibility to improve the route. Using the excel capabilities, it is possible to measure the average length of the planned routes and compare it with the average length of the real routes. In this case, the average length of planned routes is around 899 NM while in the real routes is 893NM. So, it can be seen that on average, the real routes are 6 NM shorter. This means that the planned routes are being planned

at least 6 NM longer than what they could be. Perhaps, reducing 6 NM in a route doesn't seem much, but it is relevant to notice that this is a short route and reducing 6 NM in every flight that takes this route every day can turn in a huge amount of fuel saved, less CO₂ emitted and, in the final point, money saved.

Another relevant feature of the developed tool is its ability to determine the most affected sectors that are crossed by the routes between the intended waypoints/airports. Also it shows the number of flights affected by the regulations imposed, among other details that are shown in the table below. In this case, the information presented is regarding the segment in study in this subsection, VASTO-DGO during the 1901 AIRAC.

Table 6.10: Top 10 Most Affected Sectors.

Total Delay (min)	Nº Flights Affected	Avg. per Flight (min)	Nº Days Affected	Sector Affected	Reason of Regulation
632	36	17	4	GCCCRNE	ATC Capacity
445	75	5	4	LPCEU1	ATC Capacity
142	16	8	8	LPMAD1	Equipment ATC
136	16	8	1	LPSOUTH1	ATC Capacity
74	1	74	1	LIMMSTR	Industrial Action
44	8	5	2	LECMZMUX	ATC Capacity
36	17	2	10	LFE4N	ATC Capacity
30	2	15	1	LPSOUTH1	Military Activity
28	1	28	1	LECMCJI	ATC Staffing
26	3	8	2	LSZHARR1	Weather

Analysing the Table 6.10, it is possible to conclude that just by looking to the top ten most affected sectors, the total delay induced is already over 1.000 minutes, just in one route. The major part of the regulations imposed is due to ATC Capacity which means that there aren't enough air traffic controllers or that the airspace delimited by that sector cannot hold more flights during that period of time, than the ones that are already assigned. Another reason that can induce delays is the Military Activity. This is a regulation that not always take place, and therefore if there is a sector that was affected by this kind of regulation, it doesn't mean it will be affected again soon. Also, the weather is irregular, so a sector that was heavily affected by the weather during some days, may not be affected during the next weeks.

This leads to the conclusion that some major sources of delay lie on the Air Traffic Control Services themselves due to industrial action or staffing issues. The other impacts are due to unpredicted (in the long term) causes, so there is not much to do about that. But, for example, if it becomes clear that a specific sector is frequently affected by bad weather, due to the geographic conditions, then it may become wise to try to avoid that sector in the future.

This part of the information created by the tool shows how badly is the aviation sector affected by delays, which have very negative impacts, such as unhappy passengers, loss of airport slots and even more fuel consumed. The objective with this information is to try to avoid these sectors in future route plannings, and therefore save thousands of minutes in delays per year.

6.2.2 LPPT-LFPG Route

Now that a Waypoint-Waypoint route was analysed, becomes relevant to study the behaviour of routes that have airports as initial or final points. One of the problems of analysing the efficiency based on routes that include TMA (Terminal Manoeuvring Area) points is that, depending on which runways are available at the time or due to airport congestion, the aircraft may be forced to stay on hold or fly a longer route in order to be able to land in a specific runway and, therefore, alter the final results such as route length and fuel burnt.

For this case, it was chosen the route LPPT - LFPG, which is not a very busy route but adds different perspectives on how the available runway can induce differences in the final results. In the tables below is presented the general info about the orthodromic route, which will be after used as a comparison to analyse the planned and real routes.

Table 6.11: General information about the orthodromic route.

Beg. Point	End. Point	Distance (NM)	CRCO Cost (€)
LPPT	LFPG	793.8	735.7

Table 6.12: Detailed information about the orthodromic route.

Charge Zone	Intersec. (Lat)	Intersec. (Lon)	Distance (NM)	CRCO Cost (€)	Unit Rate (€)
LP	41.671	-6.338	205.2	84.3	24.82
LE	44.206	-3.610	193.7	220.0	61.33
LF	44.206	-3.610	373.3	421.3	60.95

Analysing the Tables 6.11 and 6.12, it can be seen that the longest distance crossed in the same airspace belongs to France. When comparing the Unit Rates of both Spain and France airspaces, the difference is almost none, but when comparing with the Unit Rate for the Portuguese airspace, it represents almost 3 times the price. So in this case, it is also necessary to check if it is possible to find routes that can be cheaper than the ones already used. A good way to start that task is by analysing the most often planned routes, which are represented below.

Table 6.13: Top 10 most planned routes for the 1901 AIRAC.

Nº	Nº Flights	Length (NM)	Diff. (%)	T. Delay (min)	Avg. Delay	CRCO Cost (€)	Diff. (€)
1	19	851.5	7.3	11	1	784.3	48.6
2	12	851.5	7.3	0	0	784.3	48.6
3	12	835.8	5.3	17	1	784.3	48.6
4	9	862.4	8.6	0	0	762.6	26.9
5	9	851.5	7.3	0	0	784.3	48.6
6	8	851.5	7.3	0	0	785.3	49.6
7	7	862.4	8.6	10	1	762.6	26.9
8	6	851.5	7.3	13	2	785.3	49.5
9	6	879.3	10.8	13	2	803.9	68.1
10	4	865.8	9.1	0	0	784.3	48.6

When looking at the Table 6.13, it can be seen that there isn't exactly a dominant route since there are many different paths often chosen. And in this case there is still the same problem as in the case above of, to have a cheaper route, the length increases, which will consequently increase other associated costs, like fuel and so on.



Figure 6.5: Planned routes (green) for LPPT-LFRG.

For this case it wasn't viable the presentation of all constitutive segments of each route since it was too large, but in the figure 6.5 it is possible to have a better perception on how they are organized.

It can be seen that the routes currently chosen are all quite longer than the orthodromic route. This can be due to prohibited airspaces that force the aircraft to go around them. But this is a good example on how inefficient the route network can be, since in some cases the planned routes are about 10% longer than the most direct route, which certainly brings more costs to the airlines.

Table 6.14: Real flown routes between LPPT-LFRG.

Nº of Route	Nº of Flights	Length (NM)	Difference (%)	CRCO Cost (€)	Diff. (€)
1	5	856.8	7.93	762.6	26.9
2	3	840.6	5.89	784.3	48.6
3	3	813.2	2.44	784.3	48.6
4	2	852.9	7.45	762.6	26.9
5	2	850.6	7.16	736.5	0.8
6	2	856.3	7.86	762.7	26.9
7	2	840.8	5.92	785.3	49.5
8	2	840.6	5.89	784.3	48.6
9	2	841.9	6.07	784.3	48.6
10	2	842.1	6.08	784.3	48.6

The inefficiency mentioned above can be verified when looking at the Table 6.14, since when comparing the planned routes with the ones really flown, the aircraft tend to choose more direct routes, which is confirmed with the figure below, reducing the length of the routes from around 10% longer than the orthodromic to about 5% or 7%, which is a considerable decrease.

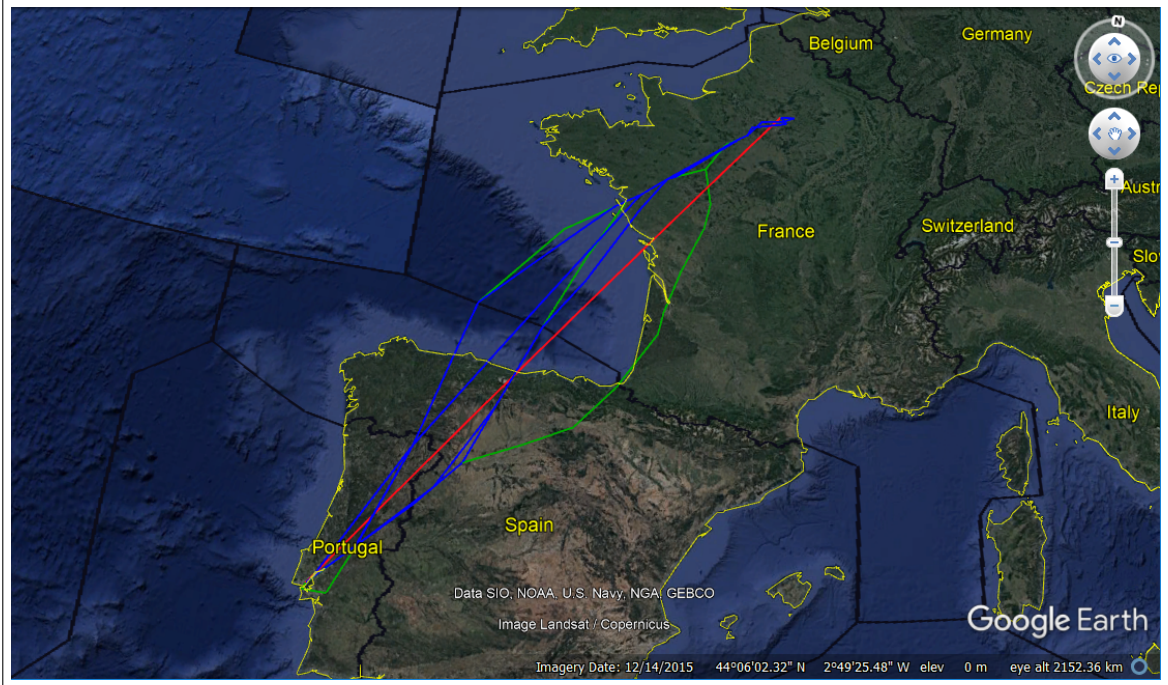


Figure 6.6: Planned/Real routes (green/blue) for LPPT-LFPG.

Table 6.15: Top 10 Most Affected Sectors.

Total Delay (min)	Nº Flights Affected	Avg. per Flight (min)	Nº Days Affected	Sector Affected	Reason of Regulation
130	12	10	5	LFPGARR1	Weather
17	1	17	1	LFRN	ATC Capacity
13	1	13	1	LECMBLI	ATC Capacity
0	1	0	1	LECMSAN	ATC Staffing
0	1	0	1	LFRAU	ATC Capacity
0	1	0	1	LFRG	ATC Staffing

Analysing the Table 6.15, which shows the most affected sectors that are crossed by the routes between the airports in study, it can be seen, similarly to the table 6.10, that the main reasons that cause delays are due to Air Traffic Services. This is a problem that happens in all airspaces and needs to be solved as much as possible in order to decrease the total amount of delays. Although the Weather is the reason of the largest delay, in 30 days (the number of days subjected to analyses in this case) only 5 days were affected, which means that it is not a very usual phenomenon, and therefore it should not be seen as a constraint to this route.

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Chapter 7

Conclusion

In this final chapter, it will be established the main conclusions and results that were possible to retrieve from the developed tool. Also, it will be presented some extra features that can be added to the tool in future developments in order to increase its capacity and overall scope of utilizations.

7.1 Achievements

In this thesis, the topics of airspace design and optimization of the current route network were addressed. It was intended with this thesis, the development of a flight efficiency evaluation tool that could act as a support for the existent tools in airspace design. Its main objectives were the gathering of historical flight data from previous flights such as planned and real flown routes, total distance, CRCO charges, regulations, delays, fuel consumption, among other relevant properties.

The FPST was then developed taking into consideration the orthodromic route between each pair of airports or waypoints selected by the user, since it is the theoretical optimum path between those 2 points, in terms of distance. These orthodromic routes act as a comparison between the different planned and real routes, both in distance and costs, being the baseline for a possible determination of the optimum route for each pair of points. Also, and acting as an upgrade for the currently available programs, it becomes possible the selection of segments of routes, such as choosing routes that cross two or three specific waypoints. This is an excellent feature since when entering or leaving the Terminal Manoeuvring Area (TMA), the flight is affected by the airport characteristics such as the runway in use, the airport congestion and so on, that could negatively affect the route statistics, which is not desired. Also, it can evaluate just a route segment that serves multiple different routes that cross that segment, allowing to study problematic sectors. Another relevant feature developed is the ability to determine which sectors were crossed by each route that were subjected to regulations. It helps to determine the incurred delays and with it, it becomes possible to try to avoid those congested sectors. Another interesting feature added to the tool was the ability to visualize the selected routes in Google Earth. This is very helpful since, when dealing with multiple different routes, if only the sequence of waypoints are given, it becomes very difficult to have a spacial visualization of how each route is designed and now it is

very easy to see how each route looks like, which airspaces are crossed or even the difference between planned and real routes.

There is also another, very important aspect which is the ability to, just by looking at the average length of the planned and real routes, see if there is a chance to reduce the planned routes length. If the average real length is smaller than the planned length, then it means that it is indeed possible to optimize that route since when flying, the pilots and ATC tend to try to find the most direct routes.

In the end, and as one of the most important features developed in the scope of this thesis is the ability to create new routes, never flown, creating new waypoints, just inserting the desired coordinates and therefore test new potential routes to optimize the current network. And, thinking about the user experience, a Graphic User Interface was developed in order to achieve a platform more user-friendly that could be very intuitive and used in an office environment more easily.

After having the tool sufficiently developed, different studies were conducted to perform the validation of the results obtained from the tool, which revealed to be as close as possible to the values obtained from the existing program, NEST. So, two different types of routes were tested, Airport-Airport and Waypoint-Waypoint. The major difference between these two cases is that in the second, the airport characteristics don't affect much the performance of the route, being more accurate to study routes this way. It was possible to determine that many routes cross congested sectors, which cause huge delays throughout the day. Many routes are planned with a certain sequence of waypoints, but during the flight itself, the pilot or ATC demand a more direct route. With this tool, it becomes possible to start planning these routes as direct as possible in order to minimize the rate of route changes while en-route.

In what concerns to the utility of this tool, after meetings with NAV (Air Navigation Service Provider) and TAP (Airline), it was possible to conclude that this tool is very useful to both players since it adds extra features to the currently available software used, allowing a better and simpler manner to collect past information and obtain statistical data for thousands of flights, which otherwise would only be possible for single flights at a time. It becomes possible to analyse new route proposals, to check if crossing the Portuguese airspace could be more profitable to the airlines and at the same time more profitable for NAV. Also, and according to TAP, this is very useful since with the tools they have, they can only access information and compare data from their own flights and, with the FPST they can see what routes other airlines are planning, and therefore look for better routes that they aren't aware of. So, despite initially this tool being developed to serve ANSPs, it revealed very interesting to other companies, such as Airlines.

7.2 Challenges

During the development of this tool, data quality issues were faced, being the most relevant, the following:

- When downloading the file from DDR2 that contains the sequence of points that define the geographic borders of each country, there were a lot of wrong points that resulted in wrong design of FIRs. Therefore, when running the algorithm to detect in which FIR a specific waypoint was located, there were multiple errors due to the waypoints that were located exactly in the border, since the algorithm couldn't identify from which FIR the flight was coming. In order to correct that, the wrong values were substituted and a new database was created and incorporated in the tool.
- The files that contain the details about each flight have lots of secondary information that is not relevant to the tool and have to be cleaned, which makes the program to run a bit slower, without however, compromising its efficiency.

7.3 Future Work

Finishing the project and had achieved its goals, there are some improvements that may be implemented in the future to increase the efficiency and capacity of the Flight Efficiency Evaluation Tool for Airspace Design, such as:

- Incorporate better algorithms in order to not only help in the historical analysis of flights in the European Airspace, but to simultaneously determine which routes can be optimized and how, based on the data available;
- Also, and with the use of artificial intelligence algorithms, create new strategic waypoints that could allow to design new routes even more efficient than the ones currently used/available, instead of being the airspace designer to try different waypoints at a time;
- If possible, gather more information to determine the price per Nautical Mile for a specific aircraft, and therefore allow to compare if an increase in distance, in order to decrease the CRCO Costs, would be profitable since not only the distance determines the final price of a route.

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Appendix A

Traffic Query - NEST

Query used in order to select only the flights that cross the following Flight Information Regions:

LPPC (Lisboa ACC), LPPO (Santa Maria Oceanic ACC), GMMM (Casablanca ACC), GCCC (Canarias ACC), LECM (Madrid ACC), LECB (Barcelona ACC), LECS (Sevilla ACC), LFBB (Bordeaux ACC), LFEE (Reims ACC), LFFF (Paris ACC), LFMM (Marseille ACC) and LFRR (Brest ACC).

Query:

(VIA S LECMFIR OR VIA S LECMUIR OR VIA S LPPCFIR) AND NOT ((DEP LEMD AND VIA ACC DAAACTA) OR (ARR LEMD AND VIA ACC DAAACTA) OR (DEP LEMG AND VIA ACC DAAACTA) OR (ARR LEMG AND VIA ACC DAAACTA) OR (ARR LEMD AND VIA S LFRRG) OR (DEP LEMD AND VIA S LFRRG) OR (ARR LEMG AND VIA S LFRRG) OR (DEP LEMG AND VIA S LFRRG) OR (ARR LEMD AND VIA S LFBBDX) OR (DEP LEMD AND VIA S LFBBDX) OR (ARR LEMD AND VIA S LFBBPZ) OR (DEP LEMD AND VIA S LFBBPZ) OR (ARR LEMG AND VIA S LFBBDX) OR (DEP LEMG AND VIA S LFBBDX) OR (DEP LEMG AND VIA ACC LECBCTAW) OR (ARR LEMD AND VIA ACC LECBCTAW) OR (DEP LEMD AND VIA ACC LECBCTAW) OR (ARR LEMD AND VIA S LFRRFIR) OR (DEP LEMD AND VIA S LFRRFIR) OR (ARR LEMG AND VIA S LFRRFIR) OR (DEP LEMG AND VIA S LFRRFIR))