

Flight Efficiency Evaluation Tool for Airspace Design

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

1. Introduction

Since 1783, with the first manned flight, it became necessary to implement methods to control the interaction 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, the Air Navigation Service Providers (ANSP) had to evolve and invest in new technologies and 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", 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 [2]. 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, which 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 the airspace in pre-defined waypoints, continuing subjected to air traffic control [4].

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:

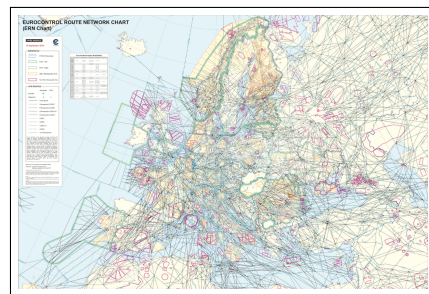


Figure 1: EUROCONTROL Route Network [5].

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 routes 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 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.

2. 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 Managers 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 [6]. 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. 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 (DDR)

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" [7].

2.3 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 [8]. Past traffic and environment data for European Airspace can be downloaded from DDR for each AIRAC.

2.4 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 [9]. 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:

$$CRCO\ Charge = UnitRate \times WeightFactor \times DistanceFactor$$

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.

2.4.1 Distance Factor

The Distance Factor is given by the great circle distance 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.

2.4.2 Weight Factor

Regarding the Weight Factor, 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, as is represented in the equation below:

$$WF = \sqrt{\frac{MTOW}{50}} \quad (1)$$

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.

2.4.3 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 [10].

2.5 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 [11]. 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 [12], which are in turn, divided into sectors and air-blocks. 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:

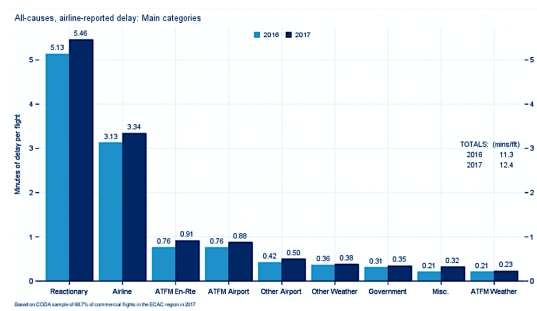


Figure 2: Airline-Reported Delay: Categories [13].

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.

2.6 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 have been released having a negative impact on the environment such as the formation of tropospheric ozone (O_3), formation of condensa-

tion trails (contrails) and cirrus clouds [14].

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 [15].

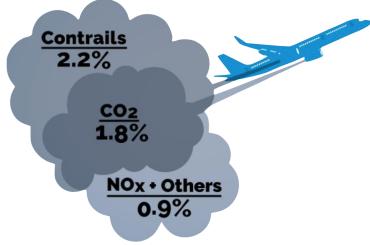


Figure 3: Impact of aircraft emissions on global warming. (Lee and Fahey, 2009)

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 [16], 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" [17], in order to develop indicators that could serve as a measuring tool to determine the environmental impact of the ATM System. The 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 used by the EUROCONTROL Performance Review Commission for its annual performance review report of air traffic management in Europe [17].

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 CO_2 emitted in each flight considering multiple factors such as type of aircraft, distance flown and the characteristics of the air traffic covered by the ETS.

3. Mathematical Background

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 [9].

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 [18]. A representation of these circles can be seen in the Figure 4.

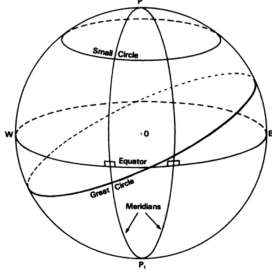


Figure 4: Representation of great circles [19].

So, in order to determine the shortest distance between two points, the following 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 [20]:

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

, 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 and, if yes, the coordinates of the intersection point, in order to determine when and where a route changes charging zone. That leads to the following algorithm [19]:

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:

$$\begin{aligned} x &= \cos(\theta) \cos(\phi) \\ y &= \sin(\theta) \cos(\phi) \\ z &= \sin(\phi) \end{aligned} \quad (2)$$

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 :

$$\begin{aligned} s_1 &= (\vec{a}_0 \times \vec{p}) \cdot \vec{t} \\ s_2 &= (\vec{a}_1 \times \vec{p}) \cdot \vec{t} \\ s_3 &= (\vec{b}_0 \times \vec{q}) \cdot \vec{t} \\ s_4 &= (\vec{b}_1 \times \vec{q}) \cdot \vec{t} \end{aligned} \quad (3)$$

In case of having $-s_1, s_2, -s_3$ and s_4 with the same signal, 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:

$$\begin{aligned} \theta &= \arctan2(y, x) \\ \phi &= \arctan2(z, \sqrt{x^2 + y^2}) \end{aligned} \quad (4)$$

4. Implementation

As was mentioned before, the aim of this thesis was the development of a tool that, in order to complement the NEST tool capabilities (a simulation software for network capacity planning and airspace design), would allow to collect only the necessary information from thousands of flights and, after perform multiple 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 chosen 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. Below, a preview of the developed tool is presented, showing how the user can insert the input data:

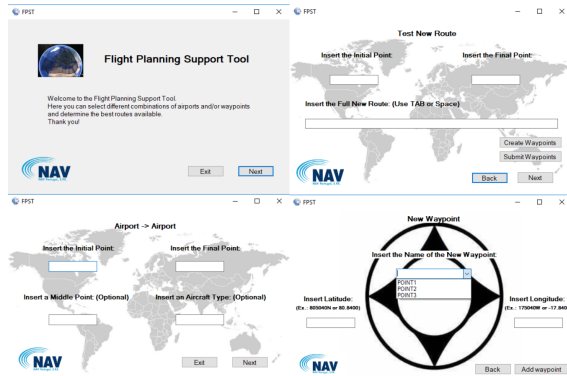


Figure 5: Different windows of the FPST.

After having the tool fully developed, several tests were performed to validate the results by comparing them with the results obtained from NEST, when having similar conditions as input. In the following section, an example of how the tool can be used is presented.

5. Results

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 1, 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. In tables 1 and 2 is the information relative to the orthodromic route:

Table 1: Orthodromic Route Information.

Beg. Point	End. Point	Distance (NM)	CRCO Cost (€)
VASTO	DGO	881.965	907.15

Table 2: Orthodromic Route Detailed Information.

Charge Zone	Intersec. (Lat)	Intersec. (Lon)	Distance (NM)	CRCO Cost (€)	Unit Rate (€)
GC	30.517	-13.567	0.533	0.61	49.96
GM	35.968	-9.195	394.012	360.95	39.86
LP	38.249	-7.141	168.564	96.15	24.82
LE	38.249	-7.141	318.857	449.44	61.33

In Table 1, a summary of the most important information about the orthodromic route is contained, like its distance and total CRCO Cost. In the table above, Table 2, is presented a more detailed 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. Also, the intersection points (latitude and longitude), with the various FIRs are presented, allowing a better understanding on how the route is designed and in what points does it enter and exit each FIR.

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 flown 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. Also, the detailed sequence of waypoints that compose each route is presented, allowing to compare each route and see how they differ. This information related to the case in study is shown in the following tables:

Table 3: Top 10 most often planned routes between VASTO-DGO.

Nº	Nº of Flights	Length (NM)	Dif. (%)	T. Delay (min)	CRCO Cost (€)	Dif. (€)	Fuel Burn (€)	Est. CO ₂ (Kg)
1	149	893.395	1.3	179	969.02	61.87	5811.06	18304.80
2	52	893.395	1.3	162	969.02	61.87	5811.06	18304.80
3	25	901.891	2.25	36	817.19	-89.96	5857.64	18451.60
4	19	901.918	2.26	125	817.19	-89.96	5857.64	18451.60
5	8	901.918	2.26	39	817.19	-89.96	5857.64	18451.60
6	7	900.392	2.09	0	856.78	-50.37	5849.42	18425.70
7	7	893.395	1.3	4	969.02	61.87	5811.06	18304.80
8	5	901.891	2.26	0	817.19	-89.96	5857.64	18451.60
9	4	904.705	2.58	0	877.32	-29.83	5873.07	18500.20
10	3	900.764	2.13	0	838.14	-69.01	5851.46	18432.10

Table 4: Waypoint sequence for the top 10 most planned routes.

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

Analysing the Tables 3 and 4, 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 3, it is possible to verify that the two (2) most frequent routes (checking the table 4, 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 Figure 6, 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.

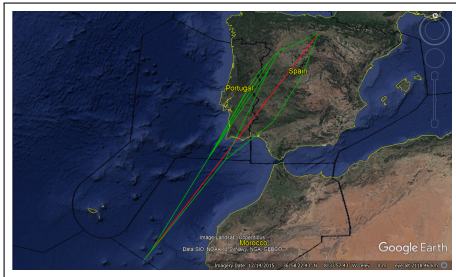


Figure 6: Planned Routes between VASTO-DGO.

Looking at the Figure 6, 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 5: Real Flights between VASTO-DGO.

N Route	N Flights	Length (NM)	Diff.(%)	CRCO Cost (€)	Diff. (€)
1	37	890.953	1.01	969.02	61.87
2	32	892.800	1.21	969.02	61.87
3	14	890.970	1.01	969.02	61.87
4	13	898.195	1.81	838.14	-69.01
5	8	894.993	1.46	867.72	-39.43
6	8	892.799	1.21	969.02	61.87
7	6	900.209	2.03	838.14	-69.01
8	5	893.332	1.27	856.78	-50.37
9	5	889.848	0.89	972.25	65.09
10	2	891.355	1.20	863.36	-43.80

Table 6: Waypoint sequence for the top 10 most flown real routes.

ROUTE														
1	VASTO	SULAM	DBMSA	IBLIV	SUNID	AKUDA	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	DGO	
2	VASTO	SULAM	DBMSA	IBLIV	SUNID	AKUDA	PESAS	OSLEP	OXACA	PARKA	SOLAX	TOLD	*SIE	
3	VASTO	SULAM	DBMSA	IBLIV	SUNID	AKUDA	OBOLQ	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	
4	VASTO	SULAM	BAROK	TOSDI	UNOVI	DGO								
5	VASTO	SULAM	BAROK	UNOVI	DGO									
6	VASTO	SULAM	DBMSA	IBLIV	SUNID	AKUDA	OBOLQ	PESAS	OSLEP	OXACA	PARKA	SOLAX	TLD	*SIE
7	VASTO	SULAM	BAROK	TOSDI	ZMR	UNOVI	DGO							
8	VASTO	SULAM	BAROK	BARDI	UNOVI	DGO								
9	VASTO	SULAM	DBMSA	IBLIV	PESAS	OSLEP	PARKA	SOLAX	TLD	*SIE	DGO			
10	VASTO	SULAM	BAROK	SOEXE	EVUBA	PORRA	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 happen 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 5 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 problem 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).

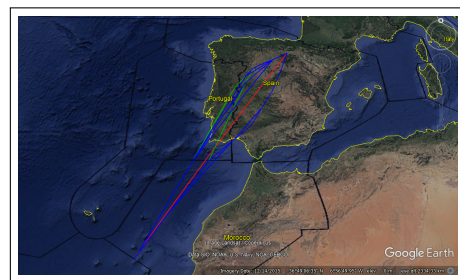


Figure 7: Real vs Planned Routes VASTO-DGO.

When looking at these tables, there is a first step to take which is to see if is 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 7. In this case, the information presented is regarding the segment in study in this subsection, VASTO-DGO during the 1901 AIRAC.

Table 7: Top 10 Most Affected Sectors.

Total Delay (min)	N Flights Affected	Avg. per Flight (min)	N 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 7, 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 ATC 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. Conclusion

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 (ANSP) 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. 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.

8. Future Work

Finishing the project and having achieved its goals, there are some improvements that may be implemented in the future to increase the efficiency and capacity of the Flight Planning Support 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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