Implementation of a Flight Planning Support Tool for Airspace Design

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Abstract — The air traffic growth of recent years has originated a demand for an improvement of airspace performance on capacity and efficiency. The current route network needs to be redesigned for more efficient routes.

The purpose of this work is the development of a tool that receives as input from the airspace design user two points, and produces outputs that provide useful information for an evaluation of the most chosen available routes between those points, as well as the calculations of the same performance indicators for the hypothetical direct route. The tool gathers historical information in order to have a larger base of information from which to retrieve the statistical data for route evaluation. It consists of a database, where the data can be updated, maintained and incremented to the most recent date, and an application that calculates the performance indicators and generates output files: a statistical data file and a visual file that allows for a graphical representation of the routes.

The developed tool enables route comparison and analysis between any navigation point and/or airport. It was possible to verify that the shortest route is not always the most cost-efficient, because of CRCO charges, and that this factor should be taken into consideration in new proposed routes.

Keywords - Air Traffic Management, Airspace Design, Route Analysis, Flight Information, Great Circle Line

I. INTRODUCTION

The continuous traffic growth observed in the last few years and predicted [1] for the near future led to a need of reformulation of the current Air Traffic Management (ATM) system. In 2008, EUROCONTROL, in its capacity of Network Manager, started the coordinated development and implementation of Free Route Airspace (FRA)[2], in which a user can plan the route between a defined entry and a defined exit point without the constrictions of a fixed route network. This initiative has the intent to improve airspace performance on capacity, efficiency and environmentally.

The Air Traffic Services (ATS) Route Network needs to progress along with the FRA development [3], for an overall airspace interconnectivity: this is particularly important in regions where there is a fixed ATS route network below the FRA, as found in the Lisbon FIR, or where there is a non-FRA area adjacent to an operational FRA area, and the definition of entry/exit points must be so that it avoids potential conflicts and won’t be damaging to capacity.

Member states and air navigation services entities are moving towards an airspace design approach that answers the demands of the current European aviation landscape [4]. Being that a cooperative effort towards the maximization of route efficiency is in place, to know and understand both the current traffic flows and the flight planning patterns becomes crucial in the decision making of airspace design operators.

Airspace Design requires modelling and simulation tools that make use of real historical data on air traffic flow. A potential airspace route network change needs to be based on a thorough analysis that validates the new scenario and evaluates the impacts on capacity and flight efficiency. Currently, the modelling and simulation resource used by EUROCONTROL and Air Navigation Service Providers (ANSP) is the NEST (Network Strategic Tool) Modelling Tool, a piece of software with visualization and analytic features, as well as simulation algorithms.

However, some features that are not available in the NEST Tool are needed for the study and redesign of the route network. The tool described in this paper addresses these needs and its outputs allow for a better route analysis.

II. THEORETICAL BACKGROUND

The study of routes will imply calculating route length, assessing intersection points of routes with charging areas frontiers and gauging distances from points to trajectories. The some assumptions that the Central Route Charges Office (CRCO) uses for the calculus of intersections between flight paths and charging area boundaries [5] are used:

- the Earth will be considered a sphere;
- the optimal path is considered the shortest path between two points on the surface of the sphere.

The value used for Earth’s radius is 6371.0 km.
A. Great circle distance

The path between two points on a sphere is the shortest arc of the great circle line, or orthodrome, which goes through those points. A great circle line results from the intersection of a plane that passes through the centre of a spherical surface.

The great circle distance can be obtained by the haversine formula [5], in which given two points on the surface of the Earth, expressed in Cartesian coordinates, the distance between those two points is given by:

\[
d = 2R \arcsin \left( \frac{\sin \frac{\phi_2 - \phi_1}{2} \cos \rho_1 \times \cos \rho_2 \times \sin \frac{\lambda_2 - \lambda_1}{2}}{\sin \frac{\lambda_2 - \lambda_1}{2}} \right)
\]

Where \(d\) is the distance, in km; \(\phi_1, \phi_2\) is the latitude of the initial and ending point, respectively (radians); \(\lambda_2, \lambda_1\) is the longitude of the initial and ending point, respectively (radians) and \(R\) is the radius of the Earth, in km.

B. Two arc cross

To determine the entry or exit point from a hypothetical orthodromic route to a charging zone, the intersection between the great circle arcs that represent the trajectory and the charging area frontier must be calculated. The method used in this thesis is the same defined by EUROCONTROL Airspace Division (DED4) [5].

The arcs are defined by two pairs of points, represented by their coordinates: \((P_1, P_2)\) for the first arc and \((P_3, P_4)\) for the second arc. The origin of the referential for this calculus coincides with the centre of the Earth.

First, the geographical coordinates are converted from radians to Cartesian coordinates (\(R\) is the Earth’s radius):

\[
\begin{align*}
  x_1 & = R \cos \text{lat}_1 \times \cos \text{lon}_1 \\
  y_1 & = R \cos \text{lat}_1 \times \sin \text{lon}_1 \\
  z_1 & = R \sin \text{lat}_1
\end{align*}
\]

Each pair of points identifies a plane that cuts the Earth by its centre. From these defining points the vector director of the plane, which is perpendicular to the plane, can be obtained by the vectorial product of the two points:

\[
V_{12} = P_1 \times P_2
\]

And the unit vector \((U_{12})\) of the vector director \((V_{12})\) as well (\(l\) is the length of the vector director):

\[
l = \sqrt{u_{12x}^2 + u_{12y}^2 + u_{12z}^2}
\]

\[
U_{12} = \frac{\begin{pmatrix} u_{12x} \\ u_{12y} \\ u_{12z} \end{pmatrix}}{l}
\]

The two planes that contain the great circle arcs, if not identical, will cross along a line that is described by the following set of equations:

\[
\begin{align*}
  (u_{12x} \times x + u_{12y} \times y + u_{12z} \times z) &= 0 \\
  (u_{34x} \times x + u_{34y} \times y + u_{34z} \times z) &= 0
\end{align*}
\]

Where \((u_{12x}, u_{12y}, u_{12z})\) are the coordinates for the unit vector director of the plane defined by the point \((P_3, P_4)\) with the centre of the Earth. The intersection line of the two planes has a vector director \(D\) that is the vectorial product of the vector directors of the planes \(U_{12}\) and \(U_{34}\):

\[
D = U_{12} \times U_{34}
\]

The intersection of the two planes and the spherical surface results in two points on the sphere, diametrically opposite. One of these two points is the intended intersection point of the path with the charging area frontier. To obtain the coordinates of these points, we need to calculate the unit vector \(S\) and its inverse \((-S)\) of the vector director \(D\), and multiply it by the Earth’s radius. \(l_0\) is the length of vector \(D\):

\[
l_0 = \sqrt{d_x^2 + d_y^2 + d_z^2}
\]

\[
S_1 = \begin{pmatrix} s_{x_1} \\ s_{y_1} \\ s_{z_1} \end{pmatrix} \quad S'_1 = \begin{pmatrix} s_{x_1} \\ s_{y_1} \\ s_{z_1} \end{pmatrix}
\]

The next step converts the Cartesian coordinates back to geographical. The arc sine function is used to determine the latitude and returns a value from \(-\frac{\pi}{2}\) to \(\frac{\pi}{2}\). The longitude is obtained with the atan2 function (2-argument arctangent), that returns an angle between \(-\pi\) and \(\pi\) that is the angle from the x axis (latitude=0, longitude=0) to the projection on the xoy plane of the ray that goes from the centre of the sphere to the point on the surface, \((R_m)\) is the Earth’s radius in meters:

\[
\begin{align*}
  \text{lat}_1 &= \arcsin(s_{x_1}) \quad \text{lat}_2 = \arcsin(s_{x_2}) \\
  \text{lon}_1 &= \text{atan2}(s_{y_1}, s_{x_1}) \times R, s_{x_1} \times R) \\
  \text{lon}_2 &= \text{atan2}(s_{y_2} \times R_m, s_{x_2} \times R_m)
\end{align*}
\]

The final step implies checking which of the opposite points is the one that corresponds to the intersection. That point will be present in both arcs. To check if the point belongs to the great circle line arcs, the length of an arc must be equal to the sum of the haversine distances of the intersection point to each extremity of the arc, that is, the following formula must be true for each arc:

\[
L_A - L_1 - L_2 = 0
\]

Where \(L_A\) is the length of the arc, \(L_1\) is the length between the intersection and the initial arc point, and \(L_2\) is the length between the final arc point and the intersection.
C. Cross-track distance

This distance corresponds to the minimum distance between a point and a great circle-path. The formula, having a great circle path defined by two points, is the following [6]:

\[ d = \text{asin}(\sin(\theta) \times \sin(\alpha_1 - \alpha_2)) \times R \] (18)

Where \( d \) is the distance (km), and the sign of this value will indicate on which side of the great circle line the point is; \( \theta \) is the angular distance from the first great circle path point to the outer point (rad); \( \alpha_1 \) is the bearing between the first point of the path and the outer point, in radians; \( \alpha_2 \) is the initial bearing of the great circle path, in radians; \( R \) is the Earth’s radius, in km.

The angular distance is obtained by the formula:

\[ \theta = \frac{H_{1-2}}{R} \] (19)

Where \( \theta \) is the angular distance (rad) and \( H_{1-2} \) is the haversine distance from the first great circle path point to the second (km).

D. Point in Polygon – Ray Casting Algorithm

Given that we have the coordinates of a point and a set of ordered points that represent the area frontier, we face a problem of point-in-polygon, for which several algorithms are available that search for a solution for any arbitrary polygon, like Hormman and Agathos indicate[7].

The polygons defined by charging zone boundaries are either convex or concave, and for this type of shape the ray-casting algorithm (that’s based on the even-odd rule) provides a solution. Given a point \( P \) and a closed polygon \( C \), defined by an array of points \( C_0, C_1, \ldots, C_n = C_0 \), a line from the point is drawn to a point that’s guaranteed to lie outside the polygon and if the number of times this line crosses the edges \( e_i = C_iC_{i+1} \) of the polygon is odd, then the point is inside the polygon; if it’s even, it’s outside[7].

E. Airline Economics

The cost per available seat per kilometre (CASK) is a way to measure airline efficiency and to compare expenses between companies in the industry.

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Figure II: RASK (revenue per available seat per kilometre) and CASK (cost per available seat per kilometre) for multiple carriers [8]

Of this total cost, according to the report performed by Oliver Wyman [8], about a third is attributed to fuel, and this cost can be directly correlated with the distance. Because the CASK depends on variables that are not related or influenced by distance flown, in order to evaluate the cost efficiency of different route lengths in this thesis we will only be looking into the Flight Operating Costs (FOC) portion that constitutes the CASK - these account for about 50% of the total cost of an airline company.

F. Air Traffic Management

Air traffic management of the European airspace users is financed through the billing of CRCO charges. The CRCO acts in the name of the EUROCONTROL Member States, and bills and collects route charges that support air navigation services and facilities [9].

The total en-route charge is a sum of the charges for each charging zone. Each of these charges is defined by the Unit Rate charge, the aircraft weight factor and the distance factor:

\[
\text{Unit Rate} \times \text{Weight Factor} \times \text{Distance Factor} = \text{Charge} \] (20)

There is a Unit Rate of charge for each Member State, which is the charge, in euros, for each distance factor and aircraft weight factor. The weight factor is obtained according to the following formula:

\[
\sqrt{\frac{\text{MTOW}}{50}} \] (21)

where MTOW is the maximum take-off weight, expressed in metric tons, rounded to the first decimal.

The distance factor is the number of kilometres of the orthodromic route between the entry and exit points of the overflown charging zone, divided by 100. In the case where the charging zone contains the departure (or arrival) airport, the distance considered is the orthodromic between the departure airport and the exit point (or the entry point and the arrival airport, respectively) minus 20 km (each).
G. DDR2 and NEST Software

The EUROCONTROL Demand Data Repository (DDR2) [11] is a web portal that contains historical information about flights in the pan-European sky. The data includes flight intentions (based on the last filed flight plan) and real flight data, and can be downloaded for visualization and analysis in the NEST tool, also available on this web portal.

The NEST (Network Strategic Tool) is a stand-alone desktop application that supports airspace design and flight planning and analysis, with features like simulation and modelling to help predict future demand and traffic distribution, and visualization and analysis of past data, with the possibility to export the data with a selection of filters[12].

The NEST Tool however doesn’t fulfill all the requirements necessary from a re-evaluation and redesign of the route network perspective. In order to analyse existing routes and measure their efficiency, there needs to be the ability to group detailed information by a longer period of time. It is also useful to compare statistics of the planned and real flights for the same timeframe, and to compare the available and most-used network routes to the orthodromic trajectory between the same initial and final points. The tool developed in this paper adds the above mentioned extra features, as well as CRCO costs for the three types of routes (planned, real and orthodromic), which is information that isn’t available in the NEST software.

III. DEVELOPMENT OF THE FLIGHT PLANNING TOOL

For the development of this tool, two different applications where used: Microsoft SQL Server Express, to store, manage and manipulate data, and Visual Studio for the development of the C++ application. Google Earth was also employed to visualize one of the output files (.kml).

Reference data from the European airspace environment and flight data are collected from the Data Demand Repository and the NEST Tool, to be imported into the database created in SQL Server. The C++ Application is the link between the user and its inputs and the database, and it is also where calculations are performed, like route length and CRCO charges. It is also this application that creates the output files.

A. Database Structure

The data is imported into an SQL database. This database is composed of multiple tables:

- Reference tables: lookup tables that contain fixed information pertinent to the database, like airport codes and coordinates, CRCO Unit Rates, navigation waypoint and their coordinates, and frontier points of each charging area as given by the DDR2 database.

- Core tables: contain all the information present in the exported flight data from the NEST Tool, for the planned flights and real flights files.

- Staging tables: hold temporary data that was treated and prepared from the base information to be used by the final application. They are only filled while executing the final program, and their data is filtered by the inputs given by the end user.

- Auxiliary tables: store intermediate information while the processes that upload and treat information are running.

B. Flight Planning Tool – C++ application

This application connects with the database to extract and transform data and executes calculations to return route statistics.

To run the executable, three inputs are requested from the user: the initial trajectory point, the ending point, and the aircraft model. The first two can be either a waypoint or the ICAO code of an airport.

The orthodromic distance between the input points is calculated and the routes available in the database that match the user criteria are selected.

The CRCO charges are calculated according to an algorithm defined by two loops:

1. First loop: to detect the charging zones that the great circle arch passes through, we find the intersection points between the arch and the charging zone frontier. The frontiers are given by the .are file from the DDR2 database in the form of a pair of coordinates followed by the charging area codes. The coordinates are sequential (i.e. the points are in consecutive order). The code loops through all the charging zones, and the purpose is to find the pair of nearest points to the great circle line for each of the areas, a point of each side of the line. This pair will be bordering points of the segment of the frontier that crosses the great circle line. In order to get them, a cycle is run for each point of the frontier, and the cross-track distance from the point to the trajectory is calculated. The sign of this distance indicates the side of the path the point is on. Therefore, if two consecutive points have a different sign, they correspond to a pair of coordinates whose segment crosses the path. These pairs are recorded during the cycle, and for each of them we have an intersection point.

2. Second loop: goes through each pair of crossing points and the two-arc cross is calculated with the input of the coordinates of the four points (2 from the frontier, 2 from the trajectory) and it returns the set of coordinates of the intersection point. The program then checks if the intersection points are along the trajectory, as opposed to anywhere on the great circle line that passes through the trajectory.
This algorithm is summarized in the following pseudocode:

**Pseudocode 1: intersection points**

1. **First loop:**
   while n <= size(CRCO_ZONES) do
     if area = CRCO_ZONES(n):
       point_keep = first point of area frontier
       previous_distance = 0
       for point Є area frontier
         point_next = get_distance from point_next to trajectory
         if |distance+previous_distance| < |distance| + |previous_distance|:
           save point_keep and point_next into VECTOR_POINTS
           previous_distance = 0
           point_keep = point_next
         else
           point_keep = point_next
           previous_distance = distance
           area = CRCO_ZONES(n+1)
       n = n+1
   end

2. **Second loop:**
   m = 0
   while m <= size(VECTOR_POINTS) do
     calculates the intersection_point between the trajectory great circle line and the great circle defined by each pair of point_keep and point_next
     if trajectory_segment Є intersection_point:
       save intersection_point to VECTOR_INTERSECTION
       save intersection_point area to ZONE_INTERSECTION
     m = m+1
   end

The travelled distance for each charging area is the difference between the trajectory length to the exit point, and the length to the exit point of the previous area. Taking the example from figure IV, the distance travelled in the LF area corresponds to \(d_2-d_1\).

The total value of the charges \(C_T\) is given by the following formula:

\[
C_T = \sum_{i=2}^{M} (d_i - d_{i-1}) \cdot U_i \cdot W
\]

Where \(M\) is the total number of crossed charging zones, \(d\) is the distance from the starting point of the route to the exit point of the charging zone \(i\), \(U\) is the Unit Rate for that area and \(W\) is the aircraft’s weight factor.

After the calculus of the orthodromic route, the top five planned and top ten real routes from the database are selected.

For each route, a cycle that goes through each route segment is executed. Each route segment is the orthodromic route between two sequential route waypoints, so the algorithm to find the intersection points is the same as that described in the previous section (Pseudocode 1).

**Pseudocode 2: selected routes intersection points**

while n <= size(selected_routes) do
  while m <= size(route_waypoints) do
    first_point = route_waypoints[m]
    second_point = route_waypoints[m+1]
    run Pseudocode 1: intersection points
    m = m+2
  end
  n = n+1
end

To calculate the CRCO charges, the considered distance is the orthodromic length between the entry and exit point of the charging zone, according to the flight plan, like the CRCO indicates [10]. These points equate to the area intersections. It does not correspond to the sum of the route segments lengths within the same area because these segments won’t describe a direct route.
IV. RESULTS

Four case studies are analyzed in this section: airport to airport, airport to waypoint, waypoint to airport and waypoint to waypoint. The airplane model considered for all case studies is a A320.

A representation of the charging zones and their relevant labels for the interpretation of the case studies is shown in figure V for reference:

![Figure V: Charging zone frontiers and labels.](image)

A. Case Study Airport-Airport: LEMD-GCLP

This case study gathers information of flights between the airport of Madrid-Barajas (LEMD) and the Gran Canaria airport (GCLP).

The route statistics output file returns a distance of 1764.81 km for the orthodromic route, and a CRCO Cost of 1123.21 €.

There are mainly two routes used in flight plans between the LEMD and GCLP airports. The CRCO Cost columns for the planned flights indicated in table I indicate that the orthodromic distance crossed in each charging zone is the same for routes 1, 4 and 5, and the same is true between routes 2 and 3.

![Figure VI: Planned trajectories for the LEMD-GCLP flight. There are mainly two routes, the top line corresponds to route 2 and 3 of table I the lower to routes 1,4 and 5. The routes overlap: the differing waypoints correspond either to different points in the take-off or approach area, or to collinear points that don’t alter the trajectory.](image)

Figure VI shows that of the two predominant trajectories there is a major difference of crossed charging zones: one crosses the LP sector, the other doesn’t. The trajectories that cross the LP area have a lesser CRCO cost – even less than the orthodromic route. This is caused by the fact that the portion of the orthodromic route that crosses the LP area is smaller, like figure VII demonstrates:

![Figure VII: Orthodromic route for LEMD-GCLP. The pins mark the intersections.](image)

The detail of each cost per charging zone can be obtained by the orthodromic route detail displayed in the file. The sum of the distances crossed by area will not equal the total length because 20 km are removed from the landing and take-off zone in order to comply with the CRCO method of calculus for the charges.

![Table II: Orthodromic route detail for LEMD-GCLP](table)

Table I: Planned flight statistics for LEMD-GCLP

<table>
<thead>
<tr>
<th>Planned Route</th>
<th>No. Flights</th>
<th>Average Length (km)</th>
<th>CRCO Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>189</td>
<td>1899.67</td>
<td>1168.75</td>
</tr>
<tr>
<td>2</td>
<td>181</td>
<td>1873.47</td>
<td>1084.15</td>
</tr>
<tr>
<td>3</td>
<td>156</td>
<td>1873.47</td>
<td>1084.15</td>
</tr>
<tr>
<td>4</td>
<td>148</td>
<td>1898.65</td>
<td>1168.75</td>
</tr>
<tr>
<td>5</td>
<td>135</td>
<td>1846.57</td>
<td>1168.75</td>
</tr>
</tbody>
</table>

To support this conclusion, the trajectories can be observed on Google Earth. As shown by image figure VI, where all the most used trajectories are selected, only two main lines are present between the airports:

![Figure VI: Planned trajectories for the LEMD-GCLP flight. There are mainly two routes, the top line corresponds to route 2 and 3 of table I the lower to routes 1,4 and 5. The routes overlap: the differing waypoints correspond either to different points in the take-off or approach area, or to collinear points that don’t alter the trajectory.](image)

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![Table II: Orthodromic route detail for LEMD-GCLP](table)

Table II: Orthodromic route detail for LEMD-GCLP

<table>
<thead>
<tr>
<th>Charging Zone</th>
<th>Distance (km)</th>
<th>CRCO Cost (€)</th>
<th>CRCO Rate (€/100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>495.098</td>
<td>440.894</td>
<td>7176</td>
</tr>
<tr>
<td>LP</td>
<td>137.888</td>
<td>68.771</td>
<td>4019</td>
</tr>
<tr>
<td>GM</td>
<td>773.839</td>
<td>382.971</td>
<td>3988</td>
</tr>
<tr>
<td>GC</td>
<td>317.984</td>
<td>230.569</td>
<td>5843</td>
</tr>
</tbody>
</table>

From the data collected we can assess that the length for a planned route is at least 4.63% higher than the orthodromic route, but for the cost the same doesn’t happen, so this could indicate, depending on the cost per km of a particular flight,
that the direct route may not be the most cost efficient for airliners.

**B. Case Study Airport-Waypoint: LFPO-SAMAR**

This case study gathers information of flights between the airport of Paris-Orly (LFPO) and an entry point for the GC area (SAMAR). The orthodromic distance is 2434.8 km and the CRCO Cost is 1616.26 €.

The most planned routes have the following characteristics:

<table>
<thead>
<tr>
<th>Planned Route</th>
<th>No. Flights</th>
<th>Average Length (km)</th>
<th>CRCO Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>2554.76</td>
<td>1579.07</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>2658.24</td>
<td>1573.25</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>2568</td>
<td>1579.07</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2678.36</td>
<td>1579.06</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>2700.88</td>
<td>1686.38</td>
</tr>
</tbody>
</table>

For all the planned routes except the fifth, that is also the longest, the CRCO charges are inferior to the direct route.

Observing figure VIII, where the planned routes are shown, it is visible that the fifth route has a longer route segment crossing the LE sector compared to the other routes, and a shorter segment crossing LP, which has a lower unit rate — so the higher cost can be justified not just by the longer distance but also due to a longer path on a higher Unit Rate area.

In figure IX there is a representation of the ninth real route (in blue, labelled “9”) and the fifth planned route (in green). The routes overlap for most of the trajectory, and it is possible to verify that the crossing points of the charging zones are the same (so the total CRCO charges have to be the same), but closer to the LFPO point the planned route describes a longer path.

Figure IX displays three routes, that correspond to an ascending order of CRCO cost: the second most used real route (labelled “2”), the orthodromic route, and the most expensive real route (ninth route). It is possible to observe that the length of the segment that crosses the LE area is also in ascending order, which explains this cost distribution.

**C. Case Study Waypoint-Airport: ECKOS-EGSS**

This case study approaches routes between the ECKOS navigation point, that is close to the Gran Canaria airport, and the Stansted airport, in London (EGSS). The orthodromic distance is 2950.89 km and the CRCO cost for the direct route is 1981.08 €.

Of the planned routes, the fifth has the smallest CRCO charges cost and the shortest distance as well. It appears to be the most cost effective, however it is the least frequently chosen of the top five. This could be an indication of another type of inefficiency of this particular route: as it can be observed from the two left images of figure X, the entry and exit points for the LE area are different from any other planned route, and they may be used in other routes that deplete the capacity for that segment.

<table>
<thead>
<tr>
<th>Planned Route</th>
<th>No. Flights</th>
<th>Average Length (km)</th>
<th>CRCO Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>3043.57</td>
<td>2093.82</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>3038.42</td>
<td>2033.6</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>3035.85</td>
<td>2044.72</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>3068.86</td>
<td>2068.56</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>3019.55</td>
<td>1975.98</td>
</tr>
</tbody>
</table>

Figure VIII: planned trajectories for the LFPO-SAMAR flight.

Figure IX: Real routes 2 and 9 represented in blue, orthodromic route represented in red. The 5th planned route is also represented in green, and most of it in underneath the route 9 since they overlap.

Of the real routes, the 9th and 10th have the highest CRCO cost, approximately the same of the 5th planned route, although the average distance is inferior.

<table>
<thead>
<tr>
<th>Real Route</th>
<th>No. Flights</th>
<th>Average Length (km)</th>
<th>CRCO Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2602.77</td>
<td>1579.07</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2532.35</td>
<td>1573.25</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2525.13</td>
<td>1579.06</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2575.74</td>
<td>1579.07</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2592.66</td>
<td>1573.25</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2614.47</td>
<td>1669.4</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>2538.57</td>
<td>1579.07</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2519.95</td>
<td>1579.07</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>2561.82</td>
<td>1686.38</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>2518.85</td>
<td>1686.37</td>
</tr>
</tbody>
</table>
D. Case Study Waypoint-Waypoint: SULAM-DELOG

This case study focuses on the routes between a waypoint in the Morocco charging zone (GM), SULAM, and an exit navigation point from the LE area, DELOG. The aircraft considered was an Airbus A320. The orthodromic length is 1697.08 km and the CRCO cost corresponds to 1008.33 €.

For the planned routes, the two most frequent are coincident and they correspond to the closest route to the orthodromic line. Despite this, these are the longest routes in total length, because although they follow closely the orthodromic route in the LP area like it is possible to observe in figure XI, there is a detour in direction when crossing the frontier with the LE area that moves the line away from the orthodrome. The CRCO costs are the minimum of all the planned routes because this is the route with the longest direct crossing distance in the LP area and the shortest in the LE area.

Table VI: Planned flight statistics for SULAM-DELOG

<table>
<thead>
<tr>
<th>Planned Route</th>
<th>No. Flights</th>
<th>Average Length (km)</th>
<th>CRCO Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>949</td>
<td>1877.79</td>
<td>1031.75</td>
</tr>
<tr>
<td>2</td>
<td>578</td>
<td>1879.19</td>
<td>1031.75</td>
</tr>
<tr>
<td>3</td>
<td>484</td>
<td>1872.9</td>
<td>1133.64</td>
</tr>
<tr>
<td>4</td>
<td>429</td>
<td>1849.46</td>
<td>1119.99</td>
</tr>
<tr>
<td>5</td>
<td>225</td>
<td>1860.85</td>
<td>1096.78</td>
</tr>
</tbody>
</table>

E. Comparative Cost Analysis

As it can be concluded from all case studies, the shortest route possible between two points can have a superior CRCO charge cost. Only a partial value of the CASK can be directly related to flight distance - for this analysis, the considered portion will be 50%.

Two types of airliners will be analyzed: the low-cost carrier and the network carrier. We will assume, for the purpose of these case studies, an average CASK for the low-cost carrier of 4 cents, and 10 cents for the network airline. The airplane model for this study will be the same used in the case studies: Airbus A320, with a 180-passenger configuration for the value airline, and a 150 for the network carrier, like suggested in Oliver Wyman’s Airline Economic Analysis report [13].

The value per kilometer for each airline will be:
- $0.04 \times 0.5 \times 180 = 3.60$ euro / km for the value carrier;
- $0.10 \times 0.5 \times 150 = 7.5$ euro / km for the network carrier.

The cost analysis for the LEMD-GCLP and LFPO-SAMAR routes demonstrate that the costs, for both types of airlines, are sorted by the same order of route length.

The planned routes with the lowest CRCO cost are the 2nd and 3rd (marked by the black frame on the graph). However, the cheapest route for both the low-cost and the network airline is the shortest, (5th). The most planned route is the least cost effective. Factors like capacity limit or delays from sector on alternative routes could be an explanation for this choice.
The planned route with the lowest CRCO cost for the LFPO-SAMAR route is the 2nd most planned. The least expensive happens to be the most planned – and shortest.

For the ECKOS-EGSS segment, although the shortest planned route is in fact the cheapest, in the case of the 2nd and 3rd most planned route, the longest of the two is the cheapest to flight overall. The same isn’t true for the network airline, so the cost per kilometers supersedes the CRCO charges.

For the SULAM-DELOG segment, the same conclusion of the shortest route being the least expensive is reached. However, the first and second must planned route have the lowest CRCO charges, and both are longer than the third route, but are cheaper overall, for both airlines. In this case, the CRCO cost may have an impact in the route chosen.

V. CONCLUSIONS

To assure efficiency in new route designs there needs to be not only a deep knowledge of the existing airspace structure and the network but also the traffic and its patterns. New entry and exit points of each charging zone, or any new navigations points in the current network, need to have into consideration the total crossing distance, because cost per kilometer is key in the industry and reducing the CO2 emissions is a goal of the ATM improvement approach. Route distance reduction however must not impair traffic flow or block sector capacity.

The developed tool manages to answer some of the needs for route design that aren’t completely fulfilled by the currently available software, and the extra features allow for a higher comprehension of the route network and it’s use by the airlines.

A. Achievements

One of the main requirements for the flight planning support tool developed was the gathering and grouping of historical flight information, by route, and the posterior selection according to the criteria of most frequently used. This was achieved for both types of information: planned and real flights. The display of route data like total distance, CRCO charges and the detail of route waypoints was also an apprehended goal.

A good route performance indicator is the orthodromic path between the same limit points, being that is the optimum when it comes to distance, and this information is also presented by this tool.

Another important accomplished feature was the ability to observe and retrieve the statistics only for the route segment between the chosen limit points, as opposed to the entire airport-to-airport trajectory. This allows for the evaluation of a route segment that may serve several different flights.

The possibility to visualize the selected routes was also crucial for the study of the network and the validation of the tool results. The .kml files generated allow for a clear understanding of the statistics and the ability to see displayed side by side the planned and the actual trajectories, which is not possible in the NEST Tool software.

B. Future Work

Although the proposed goals for the flight planning tool were achieved, extra features that contribute for a completer and more versatile tool for route design could be added:

- **Group overlapping routes**: if two routes that have a different set of registered waypoints happen to be colinear, resulting in the same trajectory, the tool will still consider them different routes. An algorithm that checks, for routes with a high percentage of common waypoints, if the
coordinates of any differing point is common to both routes could be implemented to group those routes.

- **Addition of one (or more) intermediate waypoint input by the user:** the current developed tool selects the route based on its limit points (point A to point C). The possibility for the user to add an intermediate route point B could be added, and the program would select the most used planned and real routes that cross that point as well.

- **Include flight and sector delay:** the flight delay for the real flights could be gathered and a distribution of route per average flight delays could be presented, since this is also an indicator of route performance and a symptomatic delay is evidence of an inefficiency in the designed route. Sector delay can also be a determining factor in route choice. An indicator of which sector the route crosses and the average delay it will be exposed to would be of great utility for the evaluation of sector capacity in route redesign.

- **Search of the optimum route in the available airspace:** given the two limit points, and attributing a cost per kilometer to a flight, a search algorithm that would return the optimum route could be implemented. This algorithm would have not only to take into consideration the cost input from the user but the criteria for each Flight Information Region (FIR) – whether it is a Free Route Airspace, and which are the mandatory crossing points; and for sectors where FRA is not implemented, the maximum distance acceptable between waypoints. The total cost of the flight can be the function to minimize in the search for the optimum available route, and the direct route length from each navigation point to the destiny can be considered as a heuristic function.

VI. REFERENCES