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Bachelor's Degree in Aerospace Engineering
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*Bachelor Thesis*

# ATM Performance Assessment of Minimum Climate Impact Trajectories in the European Airspace

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**Abstract**

Nowadays global warming represents an inescapable problem for human being life and entire globe. Nations from all around the planet are aware of the so called greenhouse gas emission that they are taking measurements in order to reduce the environmental impact. At the beginning, it was considered $CO_2$ as the key agent, later emission reduction was focused on $NO_x$. Currently, scientists state that persistent contrails have a non-negligible impact in global warming. This thesis present a study were ATM performance parameters are studied, such as fuel consumption, conflict, number of aircraft movements, flight time. In order to perform the analysis, four air traffic flow scenarios have been designed and simulated with TAAM, which is is a software developed by the Jeppesen Boing Company being capable of modelling air traffic and airspace. The four case studies correspond to the same low traffic day where horizontal profiles are computed as orthodromic routes between each origin and destination. The simulated scenarios are the following: *Flight Plan Case*(actual navigation procedure), *Aircraft Ceiling Case*(cruise FL at constant operational ceiling), *Minimum Climate Impact Case*(prevents contrail formation by flying at lower FL) and *Optimal Profile Case*( maximizes the position altitude by fling at continuously climbing at cruise phase) .

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# 1 Introduction

## 1.1 Motivation

Looking closer to the greenhouse effect, contrail formation is considered to be the most important parameter of aviation affecting radiation, hence, atmospheric warming. Contrails are trails of water vapour generated by aircraft engines. Commonly, they do not persist in the air for long time, although under certain atmospheric conditions they persist in the air enhancing greenhouse effect.

In fact, persistent contrails represent one magnitude higher(>10) than the $CO_2$ impact on the greenhouse effect.[1] For that reason, it is senseless to reduce $CO_2$ emissions, while flying at altitudes that are simultaneously producing persistent contrails. Thus, a balance trade-off should be searched so as to minimize the total environmental impact of commercial aviation. It is a topic that cannot be neglected when considering aircraft emissions.

Nowadays there exist several companies (e.i. Boing, Eurocontrol, TU Delft, etc) working on the development of Gate-to-Gate ATM/Airport Fast-Time Simulator softwares, which are capable of providing ATM performance of non-conventional air traffic flow scenarios. Depending on the features of the software, there can also be applied ATFM regulations. Therefore, it is capable to analyse almost any air traffic scenario without making any experimental trial in terms of ATM performance parameters. In this way, it is not only saving money in experimental tests, but also enhancing the safety of aviation sector.

**Figure** 1: Example of several persistent contrails

## 1.2 Socioeconomic Environment

Air transport is a continuously growing industry, seeking for more capacity due to its increasing demand.Indeed, in the year 2015, more than 3300 million passengers were carried and more than 100.000 flights operated everyday during this year. The Air Transport Action Group(ATAG)[2] assessed that in a 20 year future-term, the number of passengers in this industry will be doubled, increasing the economic and job supported impact, but also the environmental one. Indeed, according to the infrastructure and transport ministry of Spain, air transport contributes to 5.9% of the total Gross Domestic Product (GDP), thus, becoming one of the most socio-economically relevant sectors of Spain. Today, aircraft operations account for the 2% approximately of the $CO_2$ emissions of the global-total, and are expected to grow to 3-4% [3]. The $NO_x$ emission of the aircraft may have a pronounced impact on the chemical composition of the atmosphere.[4]

## 1.3 Regulatory Framework

International Civil Aviation Organization is a specific agency of the United Nations, responsible for ensuring the safety end efficiency flight operations of civil aviation worldwide. Moreover, there are regulatory agencies covering different areas of the globe, such as the Federal Aviation Administration(FAA, United States), European Aviation Safety Agency (EASA, Europe) or Agencia Española de Seguridad Aérea(EASA, Spain).

There has always been difficulties for both changing the legislation and reaching agreements between different countries, due to political issues. However, from several years until now, both the European Union and Eurocontrol have been working together in order to modernise the air traffic management of the European airspace, but also dealing with the reduction of environmental impact concerning the aviation, a 10% each aircraft.

In the year 2020, SESAR project is expected to come into force, thus, becoming a great opportunity to improve both the air traffic management and the aviation environmental impact.

## 1.4 Objectives

The goals of this bachelor thesis are listed below:

- Validate the different trajectories designed in a prior project leaded by the student Marcos Sanz Bravo.
- Compare the case studies in terms of economical aspects.
- Analyse in terms of ATM performance the four case studies.
- Verify whether it is feasible to implement the designed trajectories into a real scenario.

In order to perform these tasks, an airspace simulator TAAM will be used so as to retrieve information about fuel consumption, flight duration, workload and more ATM parameters. In this way, it will be possible to compare and validate the trajectories studied.

Once results from TAAM are achieved and the case studies are validated, a scientific article will be presented to EIWAC 2017, which stands for ENRI(Electronic Navigation Research Institute) INTERNATIONAL WORKSHOP on ATM/CNS. EIWAC 2017 is a conference in the area of Air Traffic Management(ATM) and Communication, Navigation and Surveillance(CNS). Also, it includes presentation for both tracks academic discussions and interchanges.

# 2 State of the Art

## 2.1 Contrail Formation Background

Contrails are line-shaped artificial water vapour clouds that are generated by the exhaust of an aircraft engine when it is shrouded into specifics ambient condition. Indeed, contrails form when the hot leaving gases get in contact with cold ambient air and , hence, forming a mixture that reaches the saturation point with respect to water. As a result, liquid drops of water are formed and, suddenly, are frozen into ice crystals. Such ambient conditions are usually found at high altitudes, above 26000 feet to be precise, where the air is extremely cold(-40 degrees Celsius approximately). For that reason, this type of contrails are only found at cruise condition.

Focusing in a turbofan engine used in civil aviation, the exhaust heat and mass of the exhaust gases leaving the engine are contained within a region called 'plume. The young plume coincides with the jet of high speed exhaust gases which initially is formed by merging the core engine jet and the jet fan bypass surrounding the core engine. At engine exit, the temperature and humidity profiles of the core and bypass jets are significantly different between them and the engine inlet flow. The reason for this phenomena is the core jet contains a large fraction of the combustion chamber heat and all of the water vapour formed resulting from burning the hydrocarbon fuel with air, whereas the bypass jet carries part of the heat but no water vapour from the combustion. Moreover, the both jets carry different velocities. Nevertheless, a few engine diameters after engine exit, a uniform turbulent jet forms in which the temperature and humidity profiles approach a similar shape. Hence, the exit jet can be approximated to a single flow with certain temperature and humidity properties, so as to study the contrail formation.[5]

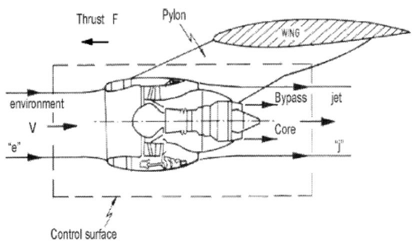


**Figure** 2: Scheme of a turbofan engine that shows the two different exhaust jets

There are three type of contrail formation:

- Short-lived Contrail: The contrail disappears as fast as the airplane goes across the sky, since the air at which the aircraft is flying has low humidity. Then, there are not enough water vapour particles in the ambient to form contrails.
- Persistent(Non-spreading) Contrail: They last longer time, even for hours. In this case, the ambient have enough humidity(high amount of particles in the air) to for contrails.

- Persistent Spreading Contrail: They not only remain for long time but also spread(due to the aircraft movement, turbulence and wind direction changes), covering a larger area.

Persistent spreading contrail can end up being a issue for the environment, concretely at high traffic spots in the upper airspace creating large artificial clouds causing a similar effect to the greenhouse effect, reducing the incoming solar radiation and the outgoing thermal radiation so that it produced heat accumulation. [6].

## 2.2 Schmidt-Appleman Model

Everyone studying contrail formation should be familiar with this model. Schmidt(1941) and later Appleman(1953) deduced a thermodynamic theory, which showed that the threshold conditions depend only on ambient pressure, humidity and the ratio of water and heat released into the exhaust plume.[7]

The Schmidt-Appleman criterion states three main assumptions with regard to the formation of visible contrails[8]:

1. Contrails are composed of ice crystals.
2. Water vapour cannot be transformed into ice without first passing through the liquid phase, hence requiring an intermediate state of saturation with respect to water.
3. A minimum visible water content of 0.004 $\frac{g}{m^3}$ is required for a short-lived trail and 0.01$\frac{g}{m^3}$ for a persistent trail. This statement, does not prove importance on the formation of the contrail, but on its persistence.

Then, contrails form in regions of airspace that have ambient relative humidity with respect to water ($RH_w$) greater than a critical value $r_{contr}$. Note that, regions with $RH_w$ greater or equal to 100 % are excluded, since clouds are already present. Moreover, concerning the life of the artificial clouds, contrails can persist when the environmental relative humidity with respect to ice$RH_i$ is greater than 100% [6].

Therefore, when the conditions defined in the equation 1 are fulfilled, persistent contrails will be formed.

$$r_{contr} \leq RH_w < 100\% \qquad and \qquad RH_i \geq 100\% \tag{1}$$

The estimated critical relative humidity for contrail formation at a given temperature $T$(in degrees Celsius) can be obtained as

$$r_{contr} = \frac{G(T - T_{contr}) + e_{sat}^{liq}(T_{contr})}{e_{sat}^{liq}(T)} \tag{2}$$

being $e_{sat}^{liq}$ the saturation vapour pressure over water at a given temperature.
The estimated threshold temperature(in degrees Celsius) is calculated as

$$T_{contr} = -46.46 + 9.43ln(G - 0.053) + 0.72ln^2(G - 0.053) \tag{3}$$

where

$$G = \frac{EI_{H_2O} C_p P}{\epsilon Q(1-\eta)} \tag{4}$$

and the parameters shown in equation 4 stand for: $EI_{H_2O}$ is the emission index of water vapour; $C_p$ is the isobaric heat capacity of air, $P$ is the ambient air pressure; $\epsilon$ is the ratio of molecular masses of water and dry air; $Q$ is the specific combustion heat; and $\eta$ is the average propulsion efficiency of the jet engine.

In order to perform a suitable analysis, this parameter must have the following values: $EI_{H_2O} = 1.25$, $C_p = 1004 J/kg \cdot K$, $\epsilon = 0.6222$, $Q = 43 \cdot 10^6 J/kg$ and $\eta = 0.15$.

The relative humidity of ice is proportional to the temperature(in degrees Celsius) and relative humidity, as it can be observed in the following formula

$$RH_i = RH_w \frac{6.0612 \cdot e^{\frac{18.102T}{249.52+T}}}{6.1162 \cdot e^{\frac{22.577T}{237.78+T}}} \tag{5}$$

In order to help a better understanding of Schmidt-Appleman criterion, two graphical examples are shown in Figures 3 and 4

In Figure 3, the continuous line represent saturation with respect to liquid and to ice, for the upper curve and the lower curve receptively. The dotted curve defines the hottest possible temperature at which contrail formation can take place, hence, contrail formation is not possible below this curve. The dashed curve correspond to the mixing of exhaust gases and the ambient air. Therefore, the light grey zone represents the critical properties of air where non-persistent contrails can take place, whereas, the dark grey zone stands for the air properties where persistent contrails can form. This last region is the one that critical attention has to be paid.

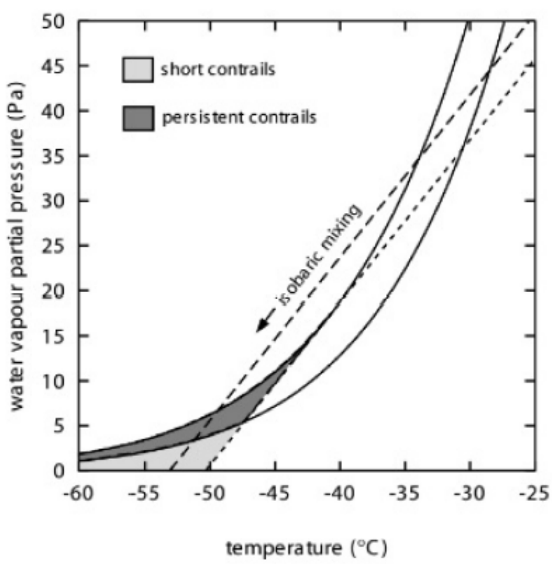


**Figure** 3: Graphical example of the Schmidt-Appleman Model

In Figure 4, it is observed that air ambient temperature distribution along the atmospheric altitude for different cases of study. The continuous dark curve, represent the standard atmospheric air temperature distribution for ISA+0(temperature linearly decreases until stratosphere is reached, where the temperature remains constant). The rest of the lines, define the air temperature distribution for different scenarios of ambient air relative humidity of water, where 1 corresponds to 100%. Therefore, contrail formation will take place between the area comprehended between the standard air ambient and the relative humidity curves.

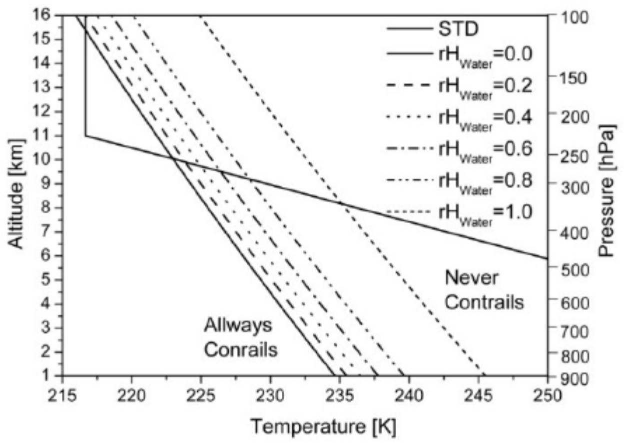


**Figure** 4: Contrail formation as a function of the atmospheric altitude [1]

It can be concluded, that the conditions for contrail formation to happen are that the ambient temperature is low and the water relative humidity in the air is high. The regions fulfilling this properties are found at least at 9000 meters altitude. Then, the higher aircrafts are enforced to fly, the higher probability of contrail formation will be.

## 2.3 Orthodromic Trajectory

In this section, it is going to be introduced the concept of an orthodromic trajectory, so as to help the reader understand the studied air traffic scenario.

An orthodrome is defined as the shortest distance between two points on a surface. Nevertheless, while being over a spherical surface, it is denoted as the shortest circled curve joining both points, in other words, it is the curve obtained by the intersection between the sphere and the plane containing the two points and the origin of the sphere. The main drawback for orthodromic routes is that the geometric track of the curves change continuously. Then, the intersection of the flight path with the different meridians is made at different angles. Although, this could seem more tedious than setting keeping a constant track angle(such as in loxodromic routes), it is ensured that the distance between departure and arrival airports is the shortest.

The *haversine formula* is an important equation in navigation, which is a more specific case of the *law of haversines*. The formula determines the circled distance between two points on a sphere given their position coordinates.

The formula is expressed in the equation 6

$$S(\lambda_i, \theta_i) = 2R \cdot arcsin\left(\sqrt{sin^2(\frac{\lambda_2 - \lambda 1}{2}) + cos(\lambda_1) \cdot cos(\lambda_2) \cdot sin^2(\frac{\theta_2 - \theta_1}{2})}\right) \quad (6)$$

where $S$ is the arc distance between the 2 points in meters, $R$ is the radius of Earth in meters, $\lambda_1$ is the latitude of point 1, $\lambda_2$ is the latitude of point 2, $\theta_1$ is the longitude of point 1 and $\theta_2$ is the longitude of point 2. Note that the coordinates are expressed in radians.

## 2.4 ATM Performance

A safe and efficient Air Traffic Management (ATM) is essential to face the challenge of increasing demand and complexity of air traffic. ATM is a very dynamic changing field regarding new techniques, innovative procedures and legal situation. In fact, the definition that ICAO provides is the following one: *Air Traffic Management is the dynamic, integrated management of air traffic and airspace management and air traffic flow management - safely, economically, and efficiently - through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-bases functions.*[9]

The Air Traffic Management can be divided in three main group:

- Airspace Management
- Air Traffic Service
- Air Traffic Flow and Capacity Management

## 2.5 TAAM - Total Airspace and Airport Modeller

*Total Airspace and Airport Modeller* (TAAM) is a product of the company JEPPESEN, which belongs to the BOING group. TAAM is a fast-time gate-to-gate simulator of airport and airspace operations. This sophisticated software tool simulates 4D (3D plus time) models of airspace and airports to facilitate decision support, planning and analysis.

Using TAAM, an analyst can develop models of airport and/or airspace; and then, evaluate the impact of changes to infrastructure, operations, or schedules. Moreover, TAAM enables the operator to identify the benefits or drawbacks when applying changes to the system such as building a new taxiway, re-designing sectors, modifying airways, changing runway configurations, or determining when saturation will be reached, among many other applications.

TAAM is capable of recording detailed simulation metrics, and presents them into an easy analysis and comparison, so decision makers can determine the best possible solution before an investment is purchased.

In addition, this product is recognised as a standard in the aviation industry, widely used by major air navigation service providers, air carriers, leading airports, aviation research establishments and universities around the globe. The university Carlos III of Madrid is the first European University acquiring this product.

Nevertheless, it is important to remind that TAAM is a tool being upgraded continuously and users might find limitations when bringing this tool to a specific scenario that the simulator has not faced yet.

## 2.6 SESAR Proyect

Single European Sky ATM Research comes from the ambitious initiative Single European Sky, leaded by the European Commission in 2004 to change the architecture of the European ATM. Eventually, SESAR looks for the evolution of European ATM system, capturing synergies and bringing both public and private stakeholders together achieving common goals.

SESAR's purpose is to build the future air traffic management system, able to deal with an expected increase of flights in Europe by the year 2020.This new system does not only have to furnish for safety, efficiency and capacity of air transport, but also need to ensure a sustainable growth.

The future of air transport needs to be environmentally respectful. It is responsibility of the aviation industry to make sure that the environmental impact of the aviation cannot be dismissed, which currently accounts for about 3% of the total European Union greenhouse gas emissions.

For that reason, one of the priorities of SESAR is to promote the reduction of environmental impact, in fact, it seeks a reduction of 10% per flight.

In addition, SESAR will introduce the so-called '4D trajectory' for developing new and more efficient air and ground systems as well as procedures. With this innovative system, the aircraft will be capable of following an agreed flight trajectory with as little change requests as possible origin to destination. This will allow airlines to fly a route in the most efficient way, minimising the environmental impact. Also, flights will follow fully optimised flight path for all phases. As a result, pilots will be capable of choosing the optimum flight path, using continuous climb, descent approaches, the most efficient altitude and speed among others. In Figure, it is graphically explained the vertical profile navigation difference between the actual procedural and optimised trajectories.

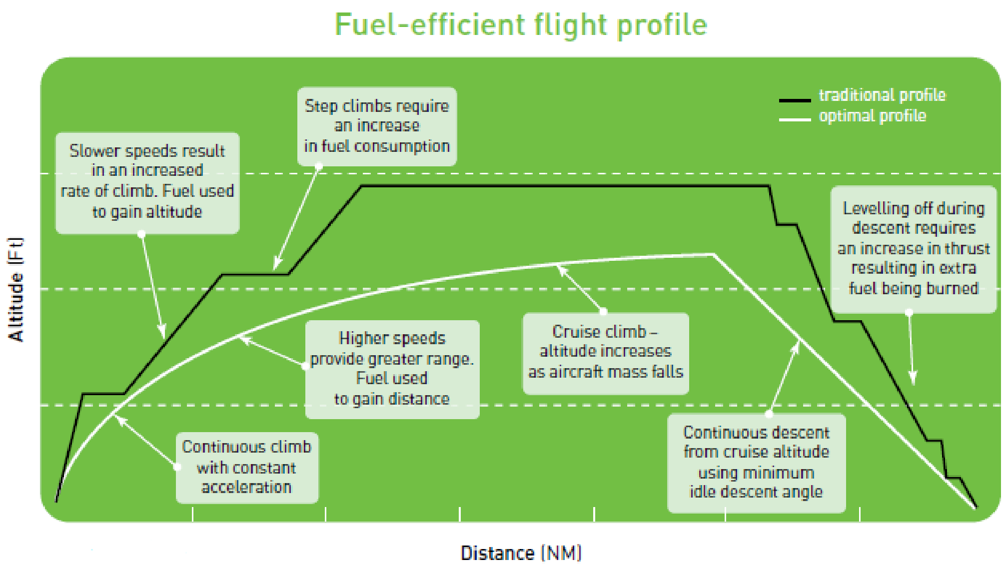


**Figure** 5: Comparison between a conventional flight trajectory and an optimised path. Source NATS company.

Therefore, this thesis could be interesting for the SESAR project since one of its objectives is to validate this sort of flight paths into a real air traffic scenario.

# 3 Methodology

In this section, it is going to be explained the process that had to be carried out in order to fulfil and obtain the results for this project. Also, the assumptions that where taken to analyse the ATM performance will be defined. See Figure 6 to help understand the procedure followed for the methodology.

1. Rearrange the data format of the trajectories into a format that TAAM program is able to read.

2. Run the simulation in TAAM, simultaneously checking with code (run with Python software) that trajectories are being generated in the desired way.

3. Generate a database using TAAM REPORTER so as to extract useful information for the ATM performance analysis.

4. Extract information from the database making use of predefined queries and post-process them using MATLAB software.

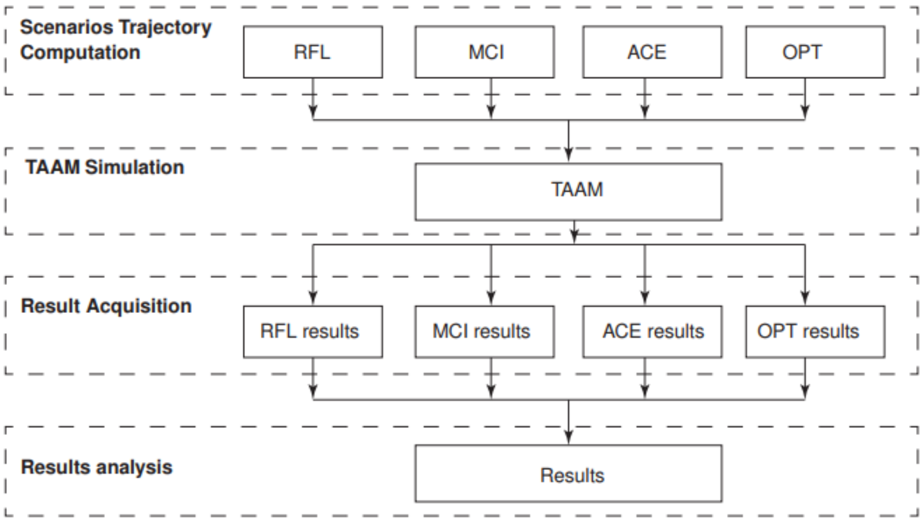


**Figure** 6: Methodology Flow Diagram.

## 3.1 Previous Work

In this section,it is going to be explained the preliminary work to this thesis. The basis of this thesis consist of 4 different trajectories designed and simulated under different models. The trajectories were designed and simulated for the bachelor thesis performed last year:

- Reference Flight Level: This trajectory takes the reference flight level indicated in the original flight plan and uses as the cruise flight level.
- Aircraft Service Ceiling: This trajectory will be the one with the lowest fuel consumption among all the possible cruising flight levels for the initial mass, avoiding level changes in cruise. Then, cruise will take place at the ceiling of initial conditions of the cruise phase of each aircraft.
- Optimal Profile Trajectory: This is the trajectory expected to be have better results in terms of fuel consumption. Indeed, optimised trajectories would lead to emission savings in all phases of flight. Continuous climb and descent paths will allow an aircraft to use only as much thrust as is needed,which means burnings less fuel.
- Minimum Climate Impact: This trajectory will be the one with lowest emission generation among a complete set of possible vertical profiles studied. The set of possible profiles goes from FL250 up to the aircraft ceiling. In fact, it cruise FL selected for this case study will be highest possible one not forming contrails. Indeed, the trajectories are computed with the cruise FL that procure less climatic impact, which is the one that minimizes the costs from Equation 13

$$TotalCost = C_{fuelBurn} + C_{contr} \tag{7}$$

where $C_{fuelBurn}$ is the fuel consumption costs per flight and $C_{contr}$ is the contrail emissions cost, that is calculated with the GWP index, which is time horizon dependant. Also, it takes $NO_x$ and $CO_2$ emission costs.

Figure 7 shows graphically the four vertical profiles of the studied trajectories. The profile *FL450* simply corresponds to the maximum altitude at which aircraft are certified and allowed to fly.

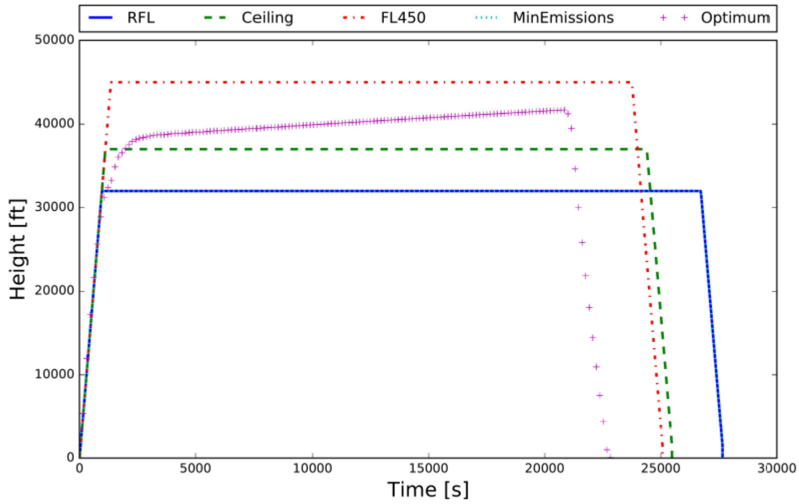


**Figure** 7: Designed vertical profiles of the flight LEMD-OMDB

In order to apply this concepts to real case, a time location was selected based on a past high traffic scenario.Indeed, it was chosen the second busiest day of an average week of the busiest month in terms of total ATM. Among the selected time span, several filters were applied to the flying aircraft in order to make the simulation feasible:

1. Non-Conventional aviation and military aviation were removed
2. Flight departing or arriving outside the Earth region covered by the NOAA data were dismissed.
3. Flights that have part of its radar(or its whole track) inside the Madrid ACC were selected.

Finally, the total number of unique flight summed the number of 2203.

The study was carried out for 3 different time horizons, to be precise, for 20, 100 and 500 years time. The difference between time slots is the taxation of $NO_x$ emissions and contrail formation. Therefore, the results in terms of economical aspects will be different. The time horizon of 20 years will be the one to be simulated in this thesis.

## 3.2 Airspace Management

### 3.2.1 Airspace Volume

It is relevant to define the categories, liabilities and services of the different airspace volumes in order to understand the air traffic management analysis performed over the designed trajectories in order to understand the air traffic management analysis performed over the designed trajectories.Then[10]:

- Movement Area: It is the area of the aerodrome devoted for the take off, landing and taxiing of aircraft, composed by the manoeuvring area and the apron.
- ATZ(Aerodrome Traffic Zone): Airspace of defined dimensions(cylinder of 5 nm with a height of 2500 ft) established around an aerodrome for the control of aerodrome traffic
- CTR(Control Zone): A controlled airspace designed to protects the approach manoeuvres, embracing ATZ and serving as connection between ATZ and CTA. It extends upwards of the Earth to a certain upper limit.
- CTA(Control Area): A controlled airspace extending up in a cylindrical shape from a specific height(at least 700 ft above the ground) above the Earth surface. Note that they shall be delimited depending the capabilities of the navigation aids used typically in the area.
- TMA(Terminal Manoeuvring Area): A control area normally established in the vicinity of one or more major aerodromes. They typically hold the SID and STAR procedures which enable aircraft to connect airways with the runway when departing or arriving.
- FIR(Flight Information Region): An airspace of defined dimensions within which flight information and alert services are provided below FL245.
- UIR(Upper Information Region):An airspace of defined dimensions within which flight information and alert services are provided above FL245 typically. In order words, it is a *Flight Information Region* which covers the upper airspace.

The influence of ground section (landing, Manoeuvring and movement area) were not taken into account for the analysis. Although it would be an attractive study, the implementation of new trajectories into the air traffic would not affect the in ground operation since each airport has predefined maximum capacity and, even though this limit is enhanced to be overpasses, it cannot happen. According to TAAM program, it would be required to implement the ground involving areas, define the ground movement of each aircraft and airport, being not feasible due to its complexity and time consumption. Indeed, this project is focused on the climb, cruise and descent phases of a flight.

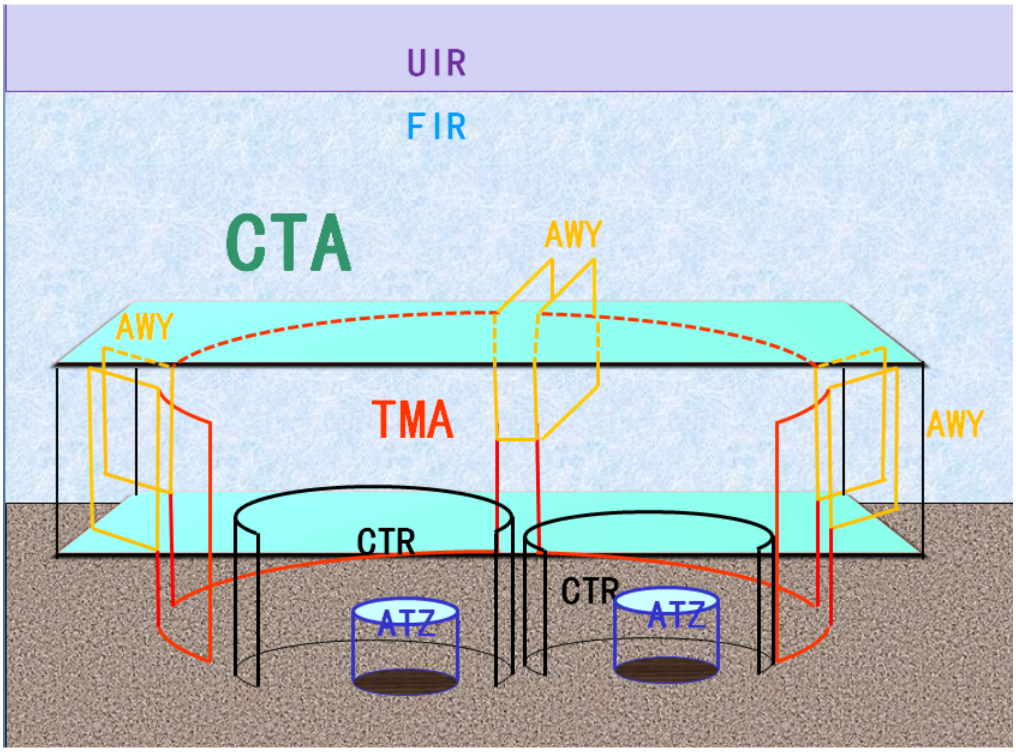


**Figure** 8: Scheme of a typical distribution of the airspace volumes.

### 3.2.2 ATS Routes

ICAO defines airspace management as the process by which airspace options are selected and applied to comply with the needs of airspace users. From an airline perspective, not all the portions of airspace are equally valued. In fact, certain aircraft operators will be more interested in overflying some areas rather than others.

ATS routes are specific routes designed for channelling the aircraft traffic as necessary as demanded for the provision of Air Traffic Services. Indeed, the ATS is responsible for organizing the different traffic flow safely and efficiently. The efficiency of a route network comes from the availability to cross concrete areas using the most direct trajectory. Hence, this efficiency is significantly affected by the architecture of the airspace, whether the it is *structured* or *non- structures*[10].

- The *structured* airspace is a system that forces aircraft to follow predefined routes, which are composed and defined by radio-aids. In this way, the complexity of traffic flow is reduced, although less efficient paths are followed.
- The *non-structured* airspace is the system that permits a free trajectory choice. In other words, when an aircraft enters into a sector, the pilot only has to define the entry and exit spots of the sector, so that the aircraft can follow the most direct way through the sector. Therefore, a more efficient navigation is pursued, even though the system is more complex. This is directly related with the Free Route concept and intended to be implemented together with the SESAR project in some areas over Europe.

In this thesis, the airspace is going to be assumed as *non-structured*. The studied trajectories where designed regardless of the actual system of airways and radio-aid because the future SESAR project enhances the Free Route concept in which the current upper airspace sectorization would disappear and a single sector would be replaced in the European airspace. In this way, the aircraft paths would be the most direct and efficient ones, in terms of covered distance.

In order to retrieve information about the airspace performance, the actual sectorization of the Spanish airspace was implemented into TAAM, regardless considering a non-structured system. It is ,thus , possible to obtain information about workload, fuel consumption, aircraft conflict and sector movements among others. Both upper European and Spanish ATC sectorization used in TAAM can be appreciated in Figures 10 and 9 respectively.

**Figure** 9: 2-D representation of the upper and lower Spanish airspace sectors .

**Figure** 10: 2-D representation of the upper European airspace sectors .

### 3.2.3 Airspace Restrictions

Currently, there are two main airspace users: civil and military operators. The use made of the airspace can seldom be significantly different, making it impossible to integrate them under the same area, requiring a segregation of airspace. Each state have sovereignty over its own airspace, and can arrange its space as desired. In other words, it can establish a set of areas through which flight is not recommended, restricted or prohibited. These areas are defined below[10]:

- *Delta Area*: Danger area. An airspace of defined dimensions within which activities dangerous to the flight of aircraft may exist at certain times.
- *Papa Area*: Prohibited area. An airspace of defined dimensions, above the land areas or territorial waters of a state, within which the flight of aircraft is denied.
- *Romeo Area*: Restricted Area. An airspace of defined dimensions above the land areas or territorial waters of a State, within which the flight of aircraft is restricted in relation to concretely specified conditions.

In this case, it was decided to neglect the presence of this type of areas for two main reasons. First of all, there is a lack of information about this sort of spaces over some of the European countries. Also, this choice was done for simplicity reasons, so that both the generation of trajectories and the simulation on TAAM program were easier.

## 3.3 Air Traffic Flow Management (ATFM)

Every airline or transport company seek for choosing the safest and most efficient route path. Therefore, usually the initial proposed trajectory envelop overlaps with others, leading to conflicts. For that reason, the initially proposed flight routes are revised and approved by the corresponding ATS providers, being consistent with their declared capacities.

The International Civil Aviation Organization (ICAO) defines ATFM as a mandatory service with the purpose of helping to a orderly, safe and expeditious air traffic flow, so as to ensure ATC capacity usage is maximized and that traffic volume is consistent with the capacities declared by the corresponding ATS provider.

The ATS authorities take different measures in order to ensure a proper air traffic flow management. Usually, these actions take place in the pre-tactical and tactical phase. These are called "regulations" and the most common are[10]:

- Ground Delays
- Level Capping
- Re-routing
- Rate Restrictions

TAAM software carries by default several options to be run in order to restrict or change the current traffic flow. These options are known as " Airspace Rules ". See Figure 11. Although TAAM offers several options for applying ATFM into the traffic flow, the task of ATFM will be neglected for this bachelor thesis, since the purpose is to simply compare the different traffic scenarios in therm of ATM performance. The application of ATFM would a future work to this project carried by the appropriate ATS provider, such as ENAIRE, ENAV, EUROCONTROL, etc.

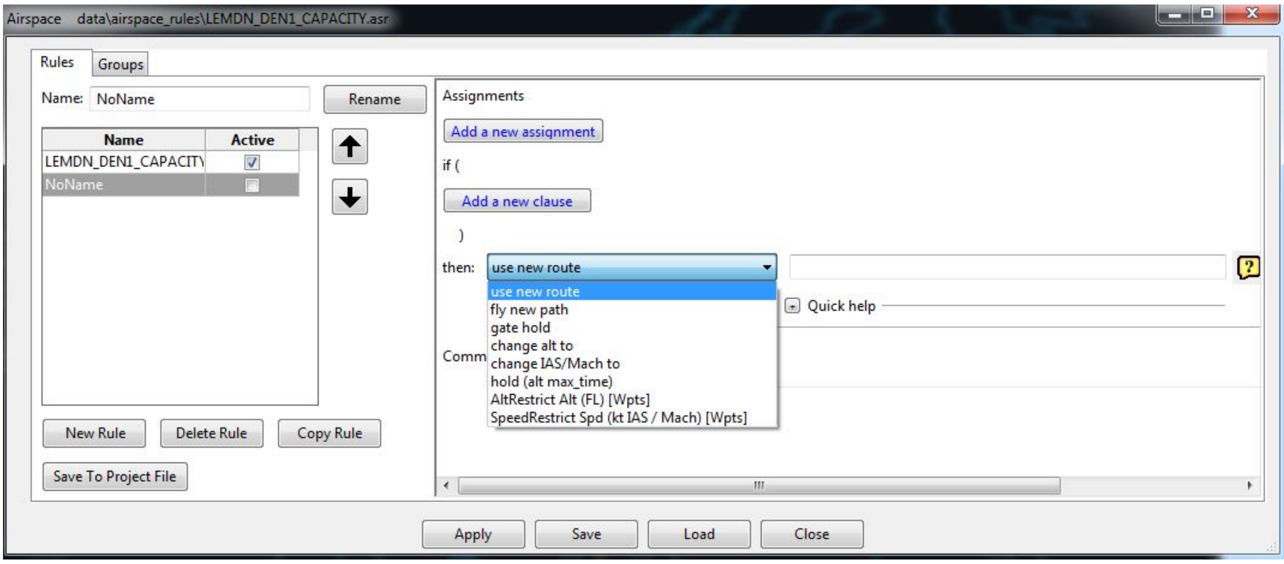


**Figure** 11: Airspace Rules workspace offered by TAAM .

## 3.4 BADA Model

The Base of Aircraft Data(BADA) is a widely used document developed by *EUROCONTROL EXPERIMENTAL CENTER* that provides a collection of ASCII files which specifies operation performance parameters, airline procedure parameters and performance summary table for more than 440 aircraft types. This information is designed for the use in trajectory simulation and prediction algorithms within the domain of Air Traffic Management. In addition, the document describes mathematical models on which the data is based. Also, it specifies the format of the files which contain the data.

The BADA version implemented in TAAM is the 3.13, while the version used to design the trajectories in previous bachelor thesis is the 3.11. It has to be mentioned that several changes and enhancements have been applied from the 3.11 version, thus, this might affect to the results obtained after the simulation with TAAM compared to the previously designed results. The changes are the following[11]:

- Full remodelling of performance characteristics of 10 aircraft type.
- Addition of performance model of 9 aircraft type.
- Update coefficients of performance model of 5 aircraft type.
- Added 4 aircraft type.
- Several Changes in the Atmospheric Effects Model.

## 3.5 Standard Deviation

The Standard deviation is a statistical measure used to quantify the amount of dispersion of a set of data values. Then, a low value for the standard deviation indicates that the data points are close to the mean of the set, whereas a high standard deviation denotes that the data points are spread over a winder range of values different from the mean. Moreover, unlike the variance, a helpful property of the standard deviation is that it is stated in the same units as the data studied.

Then, the formula for the sample standard deviation is as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})}{N-1}} \tag{8}$$

where $[x_1, x_2, ..., x_N]$ are the point values of the sample studied, $\bar{x}$ is the mean values of the points of the sample and N is the number of points of the sample.

This parameter will be used in order to compare and help to analyse the global results retrieved from the simulation, such as the burned fuel, number of conflict, flight duration or the capacity.

### 3.6 TAAM Input

TAAM software is capable of performing a simulation giving a large amount of information about fuel consumption, aircraft performance and the sectorization of airspace. Nevertheless, several steps have to be follow in order the programme to run the simulation.

In Figure 12, there are represented the steps that have to be followed, as well as the parameters that have to be defined in order to perform a simulation. TAAM offers the choice of introducing one by one each of the parameters need to define airports, waypoints, routes and schedules with a fairly clear and simple interface. This procedure could be feasible for a batch of 10 trajectories, however, this thesis involves a batch of more then 2000 trajectories . For that reason, the generation of these parameters were performed by creating a script that would generate different files that TAAM would read. This is a more efficient procedure when working with large batches of aircraft.

TAAM contains a large database of flight that have already been flown. Using this database, the software has been programmed to identify whether an aircraft is commanded to fly at its usual cruise altitude or not. This tool comes to be very useful when the user is intended to represent a realistic or already flown scenario, so that TAAM can identify any possible error when introducing the trajectory parameters. The main disadvantage is that this feature can not be deactivated, meaning that TAAM will not allow the user simulate any fictional or different scenario from the conventional ones. For that reason, it was not possible to perform the simulation of 3 of the trajectories of the thesis(the case of *Flight Plan* was correctly run since it was a real traffic).

During the month of April, it was organized a meeting with two technical engineers that had been working on the development of TAAM. The purpose of this meeting was to show improvements on the different projects that were launched throughout the year, but also try to help with issues that had arise. Then, the technical engineers proposed to generate the trajectories in a completely different way as the manuals were demanding. The trajectories would be generated using a special code that would insert the flights skipping all the steps before simulation, hence, TAAM would not modify the introduced routes. This procedure turned out to be a very tedious and time consuming since it involves running a code that both inserts all the parameters of each flight, so as to generate the trajectories one by one, rather than letting TAAM make this work, which is, in fact, designed for this task.

To be more precise with this procedure, the Figure 13 summarizes the steps to be followed. In order for this to work, 1 trajectory had to be generated in the traditional way. Then, it had to be validated and simulated by TAAM(the *validation* step is the one responsible for modifying the altitudes, since it checks that the introduced parameters are consistent with the internal database). Once the simulation of the single flight is ready, the user is capable of running the code. Finally, the simulation of the whole traffic scenario is launched.

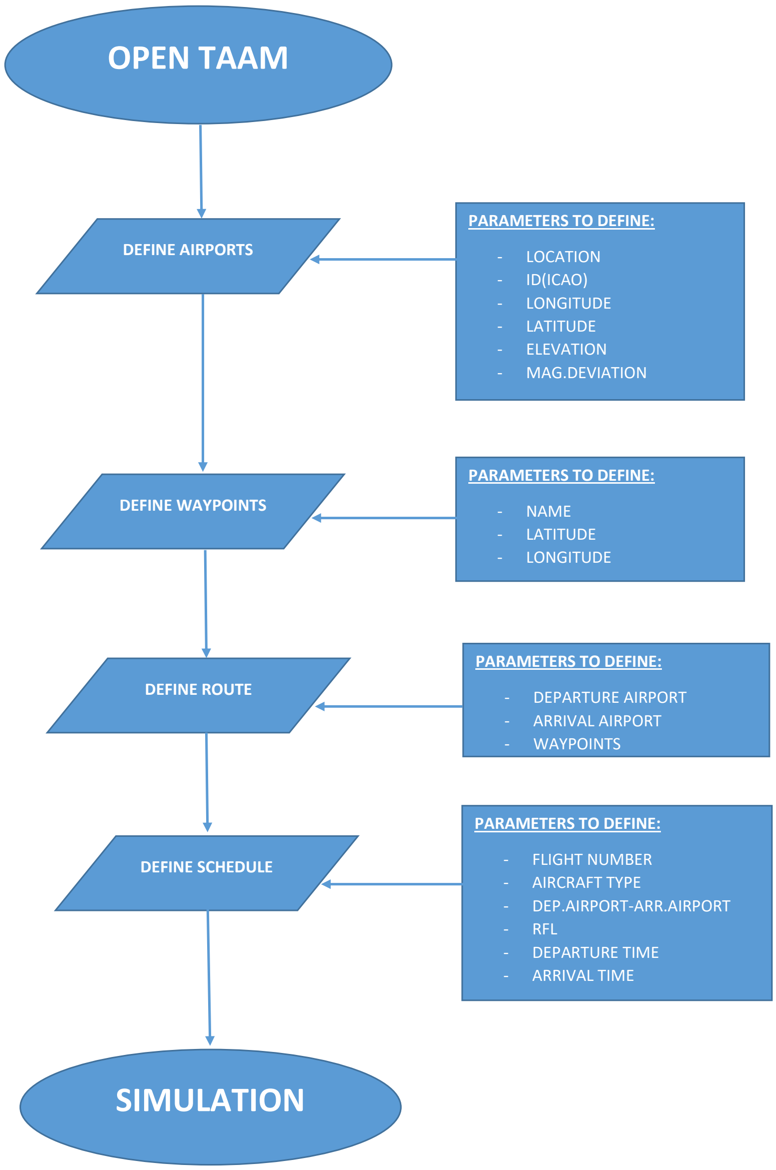


**Figure** 12: Input parameters to be defined

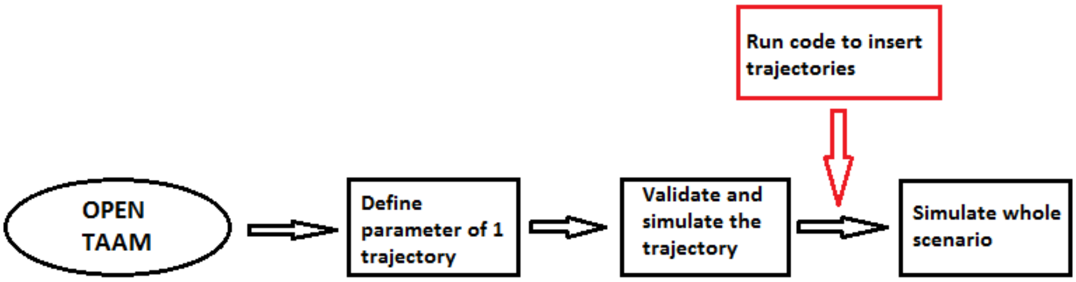


**Figure** 13: Procedure to generate and simulate the trajectories in TAAM

## 3.7 TAAM Features

### 3.7.1 Fuel Consumption

TAAM will use the BADA Model in order to compute the fuel consumption of each flight. This model classifies the aircraft in two groups: Jet/Tuboprop Engines and Piston Engines. Piston engined aircraft are not considered in this study. Three type of fuel flows are differentiated: nominal(used during climb phase), minimum(corresponds to idle thrust descent phase) and cruise(used in cruise phase).

For jet and turboprop engines,the following equations are used[12]:

$$f_{nom} = \eta \cdot T \tag{9}$$

$$f_{min} = C_{f3} \cdot (1 - \frac{H_p}{C_{f4}}) \tag{10}$$

$$f_{cr} = \eta \cdot T \cdot C_{fcr} \tag{11}$$

where $\eta$ is the thrust specific fuel consumption, T is the thrust, $H_p$[ft] is the pressure altitude, $C_{f3}$ and $C_{f4}$ are decent fuel flow factors; and $C_{fcr}$ is the cruise fuel flow factor.

The thrust specific fuel consumption is divided as follows:

$$Jet: \qquad \eta = C_{f1} \cdot (1 + \frac{V_{TAS}}{C_{f2}}) \tag{12}$$

$$Turboprop: \qquad \eta = C_{f1} \cdot (1 - \frac{V_{TAS}}{C_{f2}}) \cdot (\frac{V_{TAS}}{1000}) \tag{13}$$

where $V_{TAS}$ is the aircraft true air speed, $C_{f1}$ and $C_{f2}$ are fuel flow coefficients.

### 3.7.2 Sector Capacity

Capacity is defined as the maximum number of movements an ATS Unit is able to withstand, such as an airport or airspace sector. In other words, it is a threshold value over which safety of traffic is no longer guaranteed due to the complexity of ATM situation. Airspace capacity is not unlimited, indeed, it can be somehow optimised depending on several factors such as airspace design and flexibility; ATC system capacity; segregated airspace; availability, training and response of personnel; availability CNS infrastructure; and even the equipment and type of aircraft.[13]

Nevertheless, when analysing airspace capacity, it is interested to focus on ATC system capacity(workload for instance). There are several models used to measure and assess the parameters employed to determine capacity in order to meet air traffic demand. In a further section, it will be explained the workload model TAAM program uses.

Although computing the exact maximum number of movements established by an ATS Unit might seen to complex and tedious due to the large number of variables involved, it is of high importance to manage control the capacity of a sector, so as to perform a realistic air traffic analysis. Indeed, the maximum number of flight allowed per ATC Spanish sector is a private number that ENAIRE deals with, since it is the Spanish air traffic service provider. Then, it is not possible to know with certainty these figures.

In this thesis, the capacity of each sector will be measured in terms of aircraft movements in each sector at each instant of time. The database generated by the TAAM REPORTER was used as source of information. Using *MATLAB*, different queries will be processed so as to achieve the number of movements at each sector at each instant of time. To be more precise, TAAM REPORTER will give the number of flight per sector every 10 minutes.

### 3.7.3 Workload

Analysis on controller workload has been motivated by a desire to locate hot spots of occupational stress, eliminate operational errors and enhance safety. Although it might seem a relevant issue for research, there is no globally accepted definition for ATC Controller Workload yet. Workload measurement in ATC is often based on several parameters measured at the same time, indeed, it is a confusing term with multitude definitions. Workload cannot be measured directly, it has to be inferred from quantifiable variables. Traditionally, researchers have estimated workload throughout metrics recorded during the actual operation, such as physical interaction and physiological state of the ATC Controller.

Nevertheless, for the purpose of sectorization-based workload, the ATC workload needs to be modelled for any given volume of airspace give a certain traffic pattern. In other words, when we are interested in designing the airspace, there is no existing sector that conventional methods could apply for workload measurement. Indeed, in a large scale simulation(such as in this case) is essential to calculate variety of airspace metrics such as aircraft density, number and geometry of conflicts, number of coordination actions, altitude changes, communication actions, etc.

TAAM software uses an analytical method for workload modelling based on the traffic characteristics and sector complexity. Note that this model was developed by DFS(Deutsche Flugsicherung GmbH), which is the air traffic service provider in the region of Germany. This ATC workload model is divided into four variables[14]:

- *Horizontal Movement Workload* (HMW) is determined by the number of aircraft in the studied sector and the average flight time. Then, it can be computed from the following expression:

$$HMW = N + F \cdot T \tag{14}$$

  where N is the number of aircraft flying through the sector, T is the average flight time through the sector in minutes and F is the adjustment factor, which is defined as follows:

$$F = \Big(\frac{\sqrt{1 + 4(N-P)^2} - 1}{2(N-P)} + 1\Big)\frac{M}{2} \tag{15}$$

  Here, P is the *Turning Point Factor* which limits the workload in sectors with few flight and its units are number of flights; M is the*Movement Factor* which is used in conjunction with the average flight time and the number of aircraft in the sector.

  In order to define the *Turning Point Factor* and *Movement Factor*, this model offer a range of values for each factor. Depending on the values you choose, the results will vary significantly. See Figure 14

- The *Conflict Detection Workload* is based on conflict detection, taking the different type of conflicts and conflict severity. The conflict type is defined by the tracks of the aircraft(such as succeeding, crossing or opposite) and the flight phases(such as climbing, cruising or descending). According to the conflict severity, it is the percentage of available separation between aircraft with respect to defined minimum separation. Then, Conflict Detection Workload is computed as follows:

$$CDW = CTF \cdot CSF \cdot Q \tag{16}$$

  where CTF is the conflict type factor, CDF is the Conflict Severity Factor and Q is the number of aircraft with this conflict type and severity.

  In order to define properly the *conflict type factor*, each conflict has to be analysed individually so as to know the direction and sense of both aircraft(succeeding, crossing or opposing), but also their status(cruise, climb or descend). See Figure 14

- The *Coordination Workload* is defined by the type coordination action(such as coordination between two controlled airspace, coordination between two sectors, coordination from controlled to uncontrolled airspace,etc ). Then, it is calculated as:

$$CW = CAF \cdot U \tag{17}$$

being CAF the coordination action factor and U the number of aircraft with this action.

- The *Level Change Workload* is defined by the type of sector altitude clearance requests for level-off,begin climb and descent. Then, it is obtained with the following equation:

$$LCW = ACF \cdot R \tag{18}$$

where ACF is the altitude clearance factor and R is the number of aircraft with this clearance.The ACF will be always constant and equal to 0.3. See Figure 15

In this analysis, the *coordination workload* is going to be neglected (CW=0), since the airspace system is defined as non-structured. Then, any interaction between sectors are dismissed. Indeed, the sectorization will only be used in order to retrieve information from the simulator.[15]

Hence, the total workload is determined by the summation of the three variables defined previously:

$$TotalWorkload = \sum(HMW, CDW, LCW) \tag{19}$$

The purpose of analysing workload is not finding the factor values that will adjust better to each sector, but obtain a parametric performance measurement of a sector while flying with different scenarios. For that reason, it was decided to select the default values given by TAAM for the different factors. In this way, all the sectors will be treated equally. The default values can be observed in Figures 14 and 15.

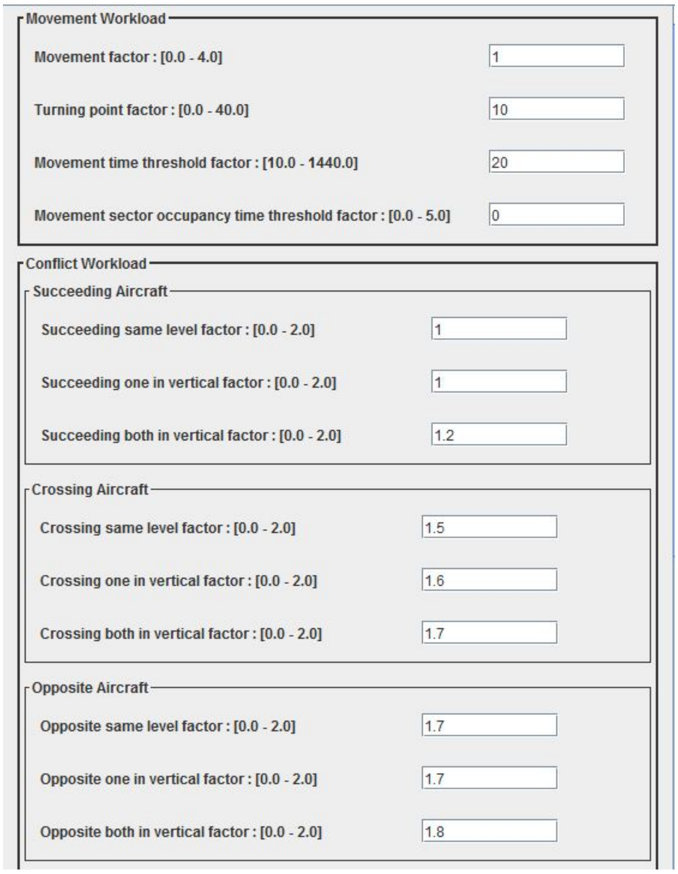


**Figure** 14: Horizontal Movement and Conflict Detection Workload Factors

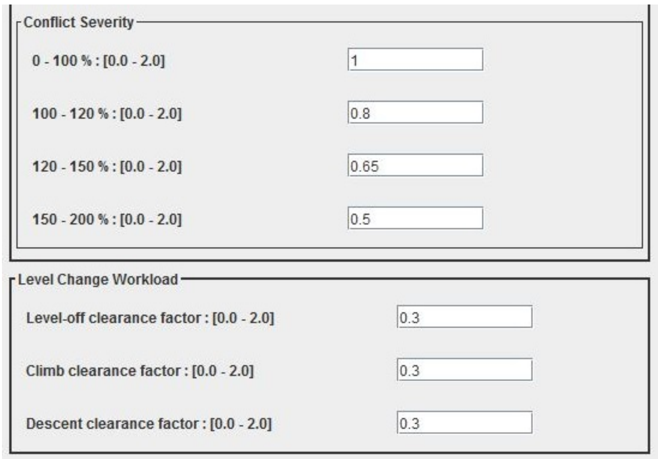


**Figure** 15: Conflict Detection and Level Change Workload Factors

### 3.7.4 Conflict Detection

TAAM offers the user a tool for detecting possible conflicts between aircraft. This becomes pretty useful when analysing a large batch of aircraft, since it is almost impossible to follow the route path of each aircraft when the simulation is being computed. Then, TAAM is capable of detecting and quantifying the number of conflicts during the simulation of an scenario. In the figure 16 it can be observed that for large number of flight traffic, it is really difficult to identify *airprox* or violations of minimum separation between aircraft.

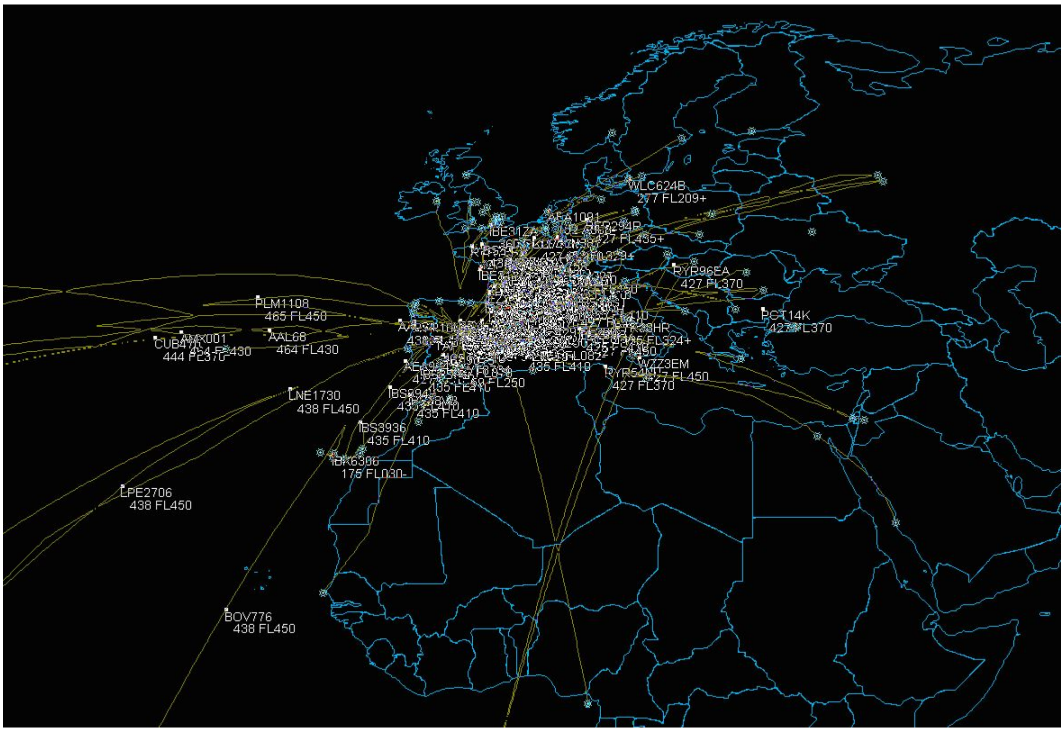

**Figure** 16: Snapshot of the studied traffic scenario

TAAM has two type of conflict detection modes: Predicted Position, which uses an adjustable *look ahead time* for conflict detection, and Current Position, which deals with the actual position of the aircraft. The mode that was chosen for this thesis is the *Predicted Position* one. Next, it is going to be defined the chosen mode to identify potential conflicts between aircraft[16].

1. When an aircraft begin the simulation, an envelope with the minimum vertical and horizontal separation distances is drawn around the flight path.

2. A list of potential conflicts between aircraft is maintained for those aircraft whose envelop overlap with others.

3. For the preliminary maintained list of possible conflicts, TAAM will calculate the *earliest possible time* the two aircraft could meet (maximum speed directly at each other) and schedules a recheck using the calculated *earliest possible time* rather than the default *look ahead time*.

4. After the recheck is completed, another check is made to see whether the envelops still overlap or not.

5. If there is still an overlapping between the envelops after last check, another *possible collision time* is computed and it is scheduled another recheck.

6. Eventually, when the *possible collision time* is within the *look head time*, TAAM will use the so called *ghost aircraft* and will compare the position of each ghost aircraft in order to determine whether there is a conflict and, if so, indicate the severity of it.See figure 17

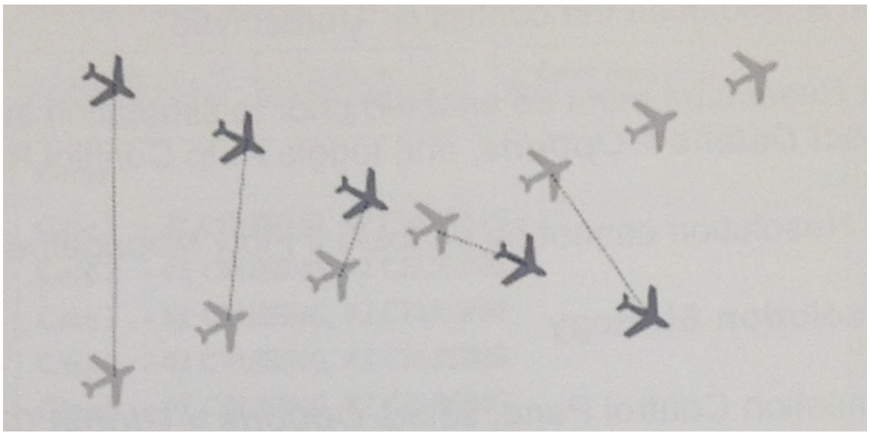

**Figure** 17: Instantaneous position comparison between actual aircraft and ghost

When reporting a conflict, TAAM is capable of determining the severity of conflict in term of distance between the two aircraft. It is taken into account both vertical and horizontal separation requirements.

In Table 1, it can be appreciated the severity classification that TAAM can report. For this project, the conflict that are going to be taken into account are the ones within a severity of 4 to 6, since it is considered by the authorities that any conflict should be cleared up before a severity of 3 is reached, in other works, any conflict should be solved before the minimum separation distance is violated.

In this thesis, for the minimum vertical separation, a value of 1000 feet has been chosen. This value corresponds to the lower level airspace, as this project covers both low and high level airspace. According to the horizontal separation, a value of 5 nautical miles was chosen, which is the common distance for en-route airspace.

In addition, note that a conflict is assessed when the distance between two aircraft is lower than 200% of the minimal established separation. Therefore, TAAM will count a conflict when the distance between two aircraft is between 100% and 200% of the established minimal separation. Also, the counting procedure corresponds to the number of conflicts assessed every hour.

**Table** 1: Reported Severity Classification

| Reported Value | Separation Achieved |
|---|---|
| 0 | Collision |
| 1 | 1-19% |
| 2 | 20-49% |
| 3 | 50-99% |
| 4 | 100-119% |
| 5 | 120-149% |
| 6 | 150-199% |

#### 3.7.5 Flight Duration

When talking about delay, it is generally referring to an Air Traffic Flow Management measurement. Indeed, if there is a predict mismatching between capacity and demand, it is common to purchase anticipated measures in order to avoid sector overloading. Most ATFM measures take place in the pre-tactical and tactical phases, modifying the initially filed Flight Plan by modifying the trajectory in terms of vertical, lateral or time intentions.

In this project, the ATFM phase will not be taken into account. Indeed, the idea for this thesis is to simulate a real traffic scenario that latter on would have to be processed by the corresponding authority, such as Eurocontrol or ENAIRE, so as to apply the corresponding regulations(e.i. ground delays, re-routing...)

Therefore, the calculation of delay will not be the real one, instead, flight arrival time of each scenario will be compared with respect to the flight plan case. Then, it will be computed the mean time difference of each case with respect to the original one, the Flight Plan Case.

Hence, the duration of flight will be calculated using the simple equation 20

$$DurationTime = ETA - ETD \tag{20}$$

where ETA is the estimated time of arrival and ETD is the estimated time of departure.

## 3.8 TAAM REPORTER

TAAM Reporter is a internal tool of the simulator that has been developed to provide rapid analysis and report generation from simulations. Starting with simulation output, Reporter enables the user to facilitate material in terms of ATM performance [14].

Reporter uses a database to marshal data from individual simulation runs, enabling analysis across different scenarios. In addition it uses all the capabilities of the database to ensure multiple users can work as a team , analysing and generating data collaboratively.

The main actions of Reporter are queries and reports. There are some already predefined ones, although it is allowed the user to develop its own. Queries are used to extract raw data in tables for export to other applications such as Matlab, while reports collate the data for presentation in tables or charts. In this thesis, only queries were used because the data retrieved from Reporter needed to be filtered and processed. The reports do not give the alternative to post-process data.

Then, the output of each simulations have to be imported into Reporter as individual projects. In this way, it is possible to retrieve data from each case, which latter will be processed using Matlab. As mentioned before, several predefined queries are provided by the program, which were very useful to obtain the required data. Note that, Indeed, the queries used are the following:

- Flight Summary
- History
- Sector Movement
- Sector Conflict
- Sector Conflict Count

Note that, the first step performed with the achieved queries was to filter the queries with a join merge of the trajectories, so that exactly the same trajectories were portrayed in the data of the queries of all cases. By processing these predefined queries with Matlab, it was achieved the total fuel consumption, the fuel consumption per flight, total number of flights, sector movements, aircraft conflicts, mean flight duration and workload by sectors.

# 4 Results

## 4.1 Represented Traffic

As it was explained previously, the traffic scenario being studied correspond to a specified high traffic day. However, in the previous work to this thesis, several filters were applied, reducing the total number of flight to 2203.

When introducing the trajectories to TAAM simulator, several issues arose. Some of them were possible to detect and mend, nevertheless, others were not. This last had an impact on the final number to flights simulated. Eventually, the final number of aircraft simulated is 1869, which represents the 85% of the initial traffic. Therefore, it can be considered that the simulated scenario represents a low traffic day, rather than a high traffic day. The main reason TAAM has rejected so many aircraft are the following:

- TAAM does not recognize the identification of some airport.
- The aircraft type database of TAAM does not recognize some of the aircraft type introduced.
- If TAAM checks that a collision is going to take place, then, it might terminate one of the flight involved in the conflict.

## 4.2 Macro-scale Analysis

### 4.2.1 Fuel Consumption

A relevant parameter that can give information whether the simulation have been computed correctly is the fuel consumption. The Table 2 shown total fuel consumption of each studied case, but also the mean fuel consumption for each flight. Also it gives the results from previous thesis in terms of fuel consumption for a 20 year time horizon, so as perform a comparison with the TAAM simulation.

Comparing the results of each case study with the Flight Plan Case:

- Minimum Climate Impact Case consumes 2,76% more than Flight Plan Case. It is consistent since generally cruise phase is flown at lower levels than Flight Plan.
- Aircraft Operational Ceiling consumes 3,52% less than Flight Plan Case. It is consistent since generally the cruise phase is flown at higher levels.
- Optimal Profile Case consumes 5,04% less that the Flight Plan Case. It is consistent since these trajectories are designed to minimize the fuel consumption.

Also, it is clear to see the significant difference in fuel consumption between the simulated study(TAAM) and designed one. Besides, the standard deviation of the mean fuel consumption for the four case studies has been performed in order to analyse the difference in the results.

$$\bar{f}_{design} = 8140,05kg \qquad \sigma_{design} = 1386kg \tag{21}$$

$$\bar{f}_{TAAM} = 5759,06kg \qquad \sigma_{TAAM} = 205,3kg \tag{22}$$

The designed standard deviation portrays the 17% of the designed mean fuel consumption, while the simulated one represents the 3,5% of the simulated mean fuel consumption. It means that the benefits in terms of fuel usage is higher in the design case. Such differences in the result could come from the different versions of the BADA model used, the loss of several trajectories when simulating in TAAM and possible incongruence in the trajectory generation of TAAM.

**Table** 2: Fuel Consumption of the four studied scenarios

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| TAAM-Total Traffic[kg] | 10.921.771 | 11.223.897 | 10.537.567 | 10.371.480 |
| TAAM-Per Flight[kg] | 5843,64 | 6005,3 | 5638,1 | 5549,2 |
| Designed-Per Flight[kg] | 8770,21 | 9143,5 | 8555,26 | 6091,22 |

### 4.2.2 Total Cost per Flight

In this section there are represented the results of total cost per flight for each case study. Indeed, the total cost is composed by the sum of fuel burn cost, the $CO_2$, $NO_x$ and contrail emission costs. To compute the fuel burn cost, the amount of fuel consumed per flight was multiplied by 1.30048 $/kg obtained from [17]. The costs for emissions were obtained from the thesis developing the studied trajectories.

In Table 3, results of the total cost per flight for each case study can be observed. Note that *Minimum Climate Impact* and *Optimal Profile* cases show the best behaviour in economical aspects. In fact, the *Minimum Climate Impact* has the lowest cost, since a extremely low contrail formation cost is achieved. This is a very positive result for both the environment and airlines. Indeed, international regulatory authorities are already studying the application of a new contrail formation tax.

**Table** 3: Total Cost ($) per flight in a 20 year time horizon.

| **Case Study** | Fuel | $CO_2$ | $NO_x$ | **Contrail** | **Total** |
|---|---|---|---|---|---|
| Flight Plan | 7599.54 | 740.58 | 1050.51 | 1737.71 | 11128.34 |
| Aircraft Ceiling | 7332.24 | 692.66 | 982.92 | 1192.83 | 10204.65 |
| Min.Climate Impact | 7809.77 | 823.39 | 1187.78 | 53.25 | 9874.19 |
| Optimal Profile | 7216.62 | 399.37 | 467.29 | 1836.50 | 9919.78 |

### 4.2.3 Flight Duration

In Table 4, there can be observed the mean duration flight time calculated for all the traffic flow cases.

**Table** 4: Mean flight duration time for each case study

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Mean Time[s] | 8407,24 | 8438,78 | 8447,15 | 12316,87 |
| Mean Time[min] | 140,12 | 140,64 | 140,78 | 205,28 |

The value obtained for both the mean time and the standard deviation of the mean duration values of the 4 studied cases are:

$$t_{mean} = 156,7085 \quad minutes \qquad and \qquad \sigma = 32,38 \quad minutes \tag{23}$$

The standard deviation obtained is approximately 20% of the total mean flight duration. It means that the differences in time between cases are relevant. Indeed, it is the *Optimal Profile Case* that has a mean delay of more than 1 hour compared with the other cases. On the other hand, the remaining cases arrive almost at the same time. So the *Minimum Climate Impact Case* will arrive its destination as the actual Flight Plan.

### 4.2.4 Conflicts

This section seeks for the comparison of each case study in terms of conflict detection. The Table 5 shows total number of conflicts counted for each simulation.

As it was expected, Flight Plan Case registers the lowest number of conflicts since its flight paths have already been filtered through ATFM regulations, so as to avoid conflicts. Then, Aircraft Operational Ceiling Case assessed the maximum value, as aircraft are intended to fly at the highest possible flight levels, thus, aircraft cruise paths overlap. The cases of Minimum Climate Impact and Optimal Profile shown a similar values in between the prior maximum and minimum cases. Also:

$$\bar{c} = 2790 \quad conflicts \qquad \sigma = 775 \quad conflicts \tag{24}$$

The standard deviation is proving that there are large differences in the conflicts depending on the case selected. Hence, number of conflict is a parameter to take into account.

**Table** 5: Total number of conflict along the simulation for all the cases studied

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Conflicts | 1.737 | 2.958 | 3.603 | 2.860 |

### 4.2.5 Spanish Airspace - LE

LE sector gathers all the Spanish ACC sectors. The altitude limits defined in TAAM go from 0 to 46000 feet, considering both upper and lower airspace.

The Table 6 gathers quantitative information about the number of movements and conflicts that take place along the simulation of the four cases. Note that a movement is defined as the number of aircraft registered flying in the studied airspace sector every hour.

The maximum number of movements is registered at the *Optimal Profile* case because the aircraft take more time to reach the destination. The maximum number of conflict are registered at *Aircraft Ceiling* case, since aircraft are forced to flight at similar flight levels.

The Figures 18, 19, 20 show the capacity, conflict and workload evolution along the simulation time. In these figure it can be reflected the data displayed in Table 6. Note that the curve for *Minimum Climate Impact* is shifted downwards due to the low number of movements assessed. This is a TAAM incongruence, in which TAAM misunderstood the information because both files for the Spanish ATC sectors and European upper airspace sectors were load at the same time. Se that in the rest macro-scale sector analysis no weird results are observed. Also, the workload curve shown a similar shape to the capacity curve because the workload model strongly depends on the sector movement.

**Table** 6: Total number of conflict and movements along the simulation for LP sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 3185 | 1903 | 3172 | 3487 |
| Total nº Conflicts | 79 | 21 | 161 | 99 |

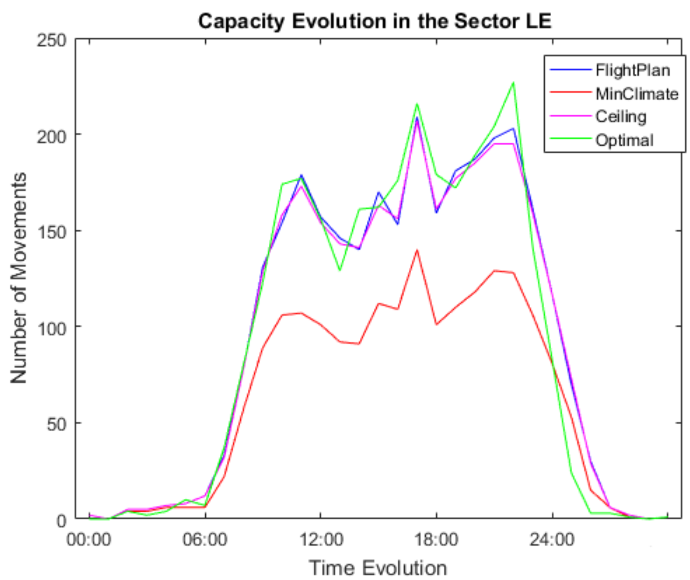


**Figure** 18: Aircraft movement evolution over the Spanish airspace

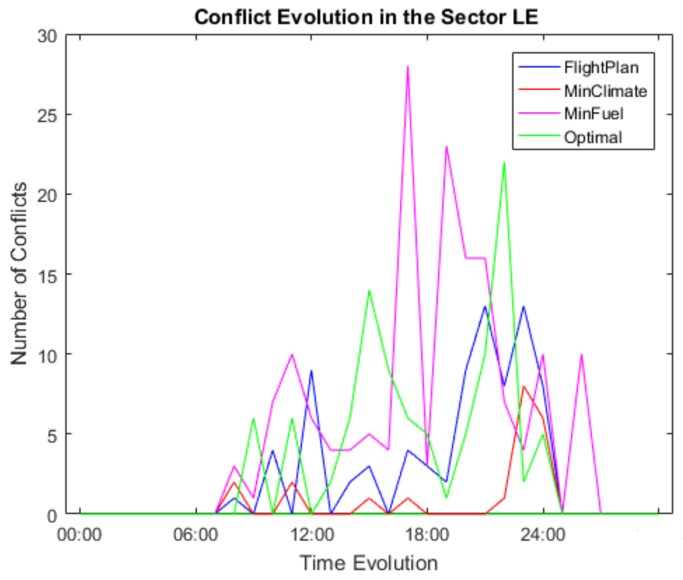


**Figure** 19: Aircraft conflict evolution over the Spanish airspace


**Figure** 20: Workload evolution over the Spanish airspace

### 4.2.6 Portuguese Airspace - LP

LP corresponds to the airspace of Portugal. The altitude limits defined in TAAM go from 0 to 46000 feet, taking both upper and lower airspace.

According to the information of Table 7, the highest number of conflict is registered at *Aircraft Ceiling Case* as expected, but the minimum values are achieved for the *Minimum Climate Impact* and *Optimal Profile* Cases instead of the *Flight Plan* Case. Therefore, in the Portuguese airspace, it could be beneficial in terms of conflict formation to apply a new air navigation model rather than the actual flight plan.

The Figures 21 and 22 represent graphically the results gathered in Table 7, in which *Optimal Profile* Case shows a different behaviour for the sector movements and a less conflictive scenario together with the *Minimum Climate Impact* case study.

Moreover, note that in the Figure 23, *Optimal Profile* case seems to generate the lowest workload. This phenomena is fairly positive considering the application of *Optimal Profile* trajectories to the real traffic.

**Table** 7: Total number of conflict and movements along the simulation for LP sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 1547 | 1540 | 1545 | 1418 |
| Total nº Conflicts | 283 | 262 | 294 | 266 |

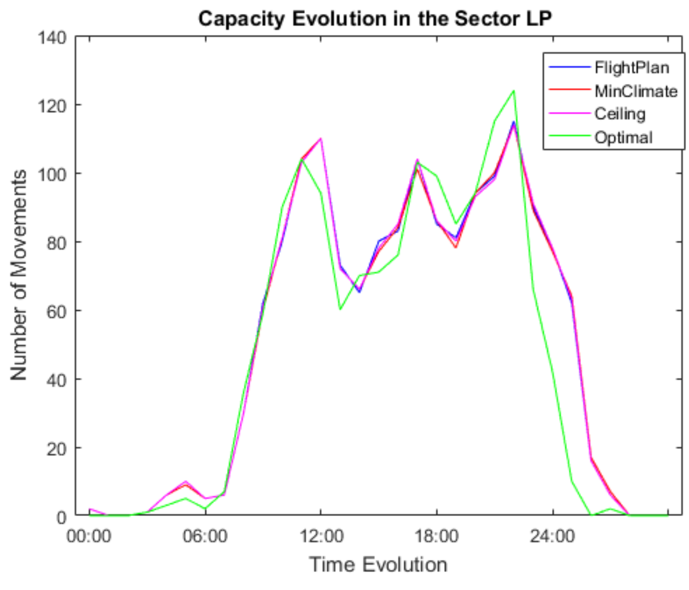


**Figure** 21: Aircraft movement evolution over the Portuguese airspace

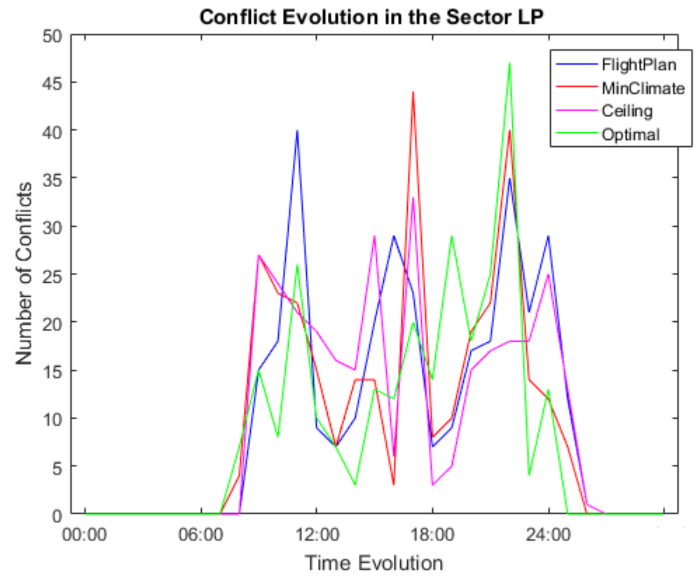


**Figure** 22: Aircraft conflict evolution over the Portuguese airspace


**Figure** 23: Workload evolution over the Portuguese airspace

### 4.2.7 French Airspace - LF

LF is the sector concerning French airspace. The altitude limits defined in TAAM go from 0 to 46000 feet, considering both upper and lower airspace.

In Table 8, the global results of LF sector movements and conflicts are shown. Note that the total number of movements are fairly similar for all case studies. According to the conflict count, it is clear to see that the implementation of *Minimum Climate Impact*, *Optimal Profile* and *Service Ceiling* trajectories portray a detrimental performance in terms of conflict detection. However, it has to be mentioned that these trajectories have not been generated with ATFM regulations.

Figures 24 and 25 represent graphically the results displayed in Table 8, where the there is almost no difference in aircraft movement, although *Flight Plan* case study generates much less conflicts.

**Table** 8: Total number of conflict and movements along the simulation for LF sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 2991 | 2987 | 2990 | 2840 |
| Total nº Conflicts | 475 | 1217 | 1453 | 1026 |

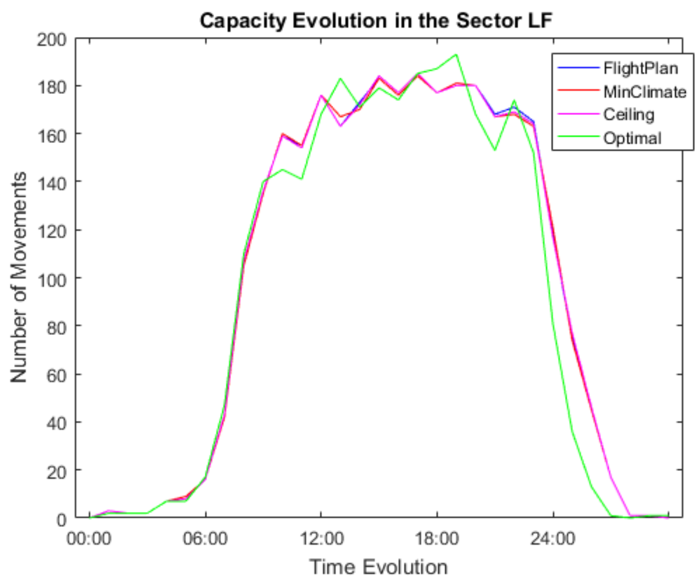


**Figure** 24: Aircraft movement evolution over the French airspace

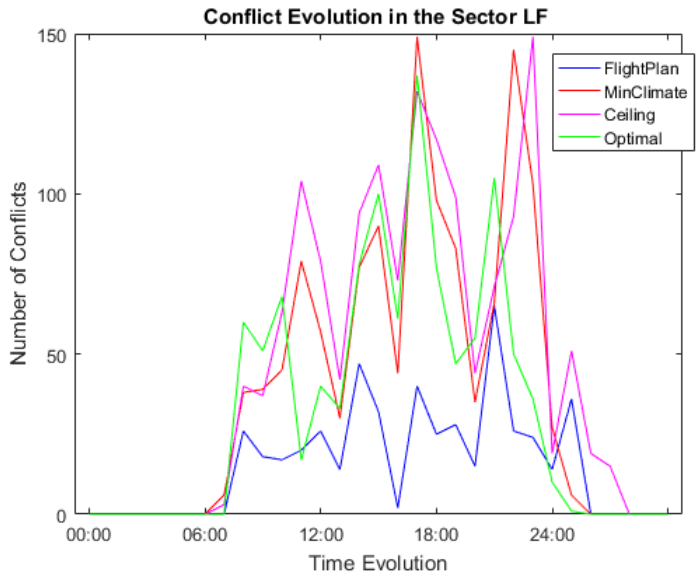


**Figure** 25: Aircraft conflict evolution over the French airspace

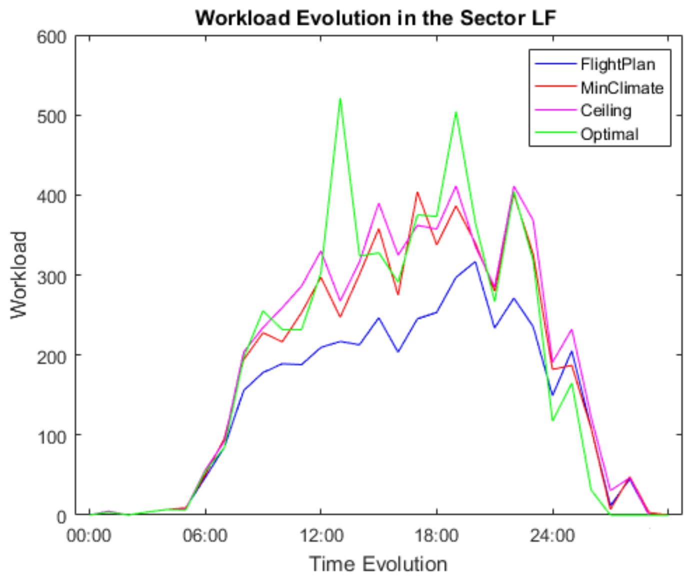


**Figure** 26: Workload evolution over the French airspace

## 4.3 Micro-scale Analysis

In order to perform a more specific and lower scale study, a strategic selection of sectors was carried out. The selection consisted on identifying which sectors from ATC Spanish sectorization were more critical in terms of aircraft movement and conflict detection for all the case studies. Then, the sector that met the requirements are: LECM1-BLU1, LECM2-TLU1 and LEMDN-DEN1.

By analysing smaller areas, it will be capable to identify more specific performance characteristics of the four trajectories, but also how the different type of sectors would respond to a new air traffic flow.

Maximum capacity of a sector can vary depending on several factors, such as the size, function on the sector, limiting altitudes, etc. Typically, the maximum number of movements that an ATS provider can withstand in a sector promoting safe traffic flow is between 40 and 60 approximately. For this bachelor thesis, it was chosen 40, since the simulated scenario represents a low traffic day.

### 4.3.1 LECM1-BLU1 Sector

LECM1-BLU1 is an upper airspace devoted sector, whose limiting altitudes are 34500 to 46000 feet. Then, this sector will mainly register fights in cruise phase. The shape and location in the Spanish sectorization can be observed in the Figure 41 at Appendix.

Both *Flight Plan* and *Minimum Climate Impact* sum less movements and, thus, less conflicts too. This phenomena take place because the cruise FL of the prior mentioned case studies, seldom correspond to the highest possible FL. Hence, as LECM1-BLU1 is an en-route sector, aircraft might fly below the analysed sector. It can also be reflected in the sector workload , where *Flight Plan* faces the minimum followed by the *Minimum Climate Impact* case, see Figure 29.

In Figure 27, note that capacity limit is overpassed by *Optimal* and *Ceiling* cases.

**Table** 9: Total number of conflict and movements along the simulation for LECM1-BLU1 sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 461 | 486 | 621 | 557 |
| Total nº Conflicts | 36 | 43 | 90 | 79 |

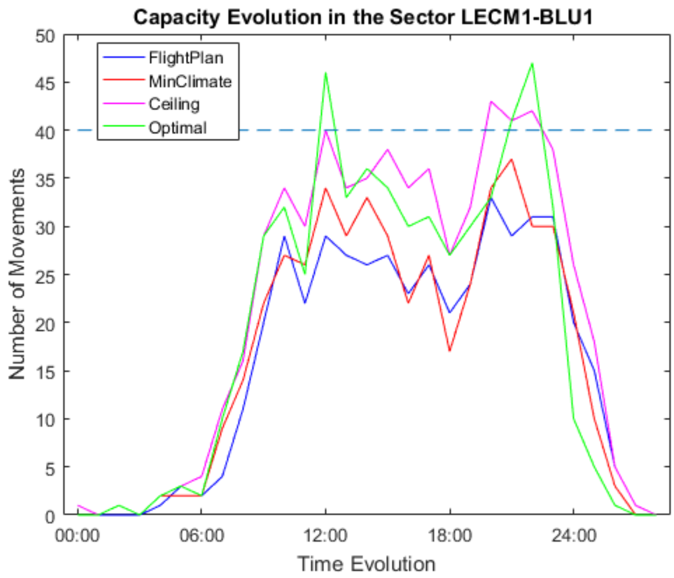


**Figure** 27: Sector Capacity evolution over the LECM1-BLU1 sector

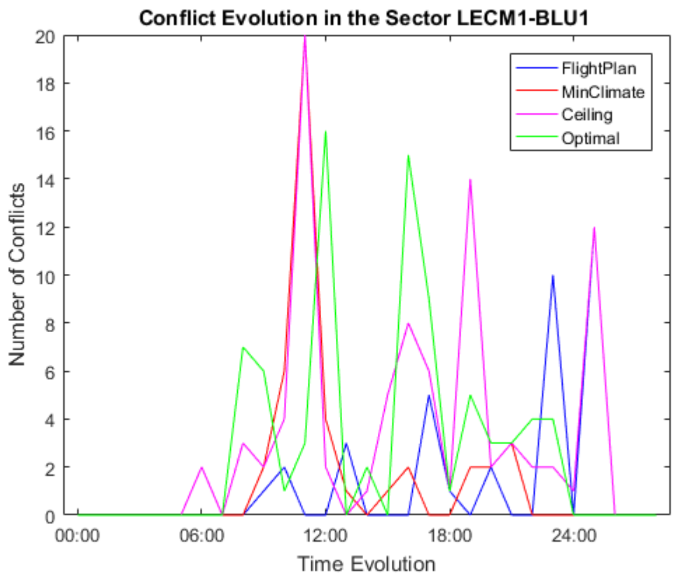


**Figure** 28: Conflict evolution over the LECM1-BLU1 sector

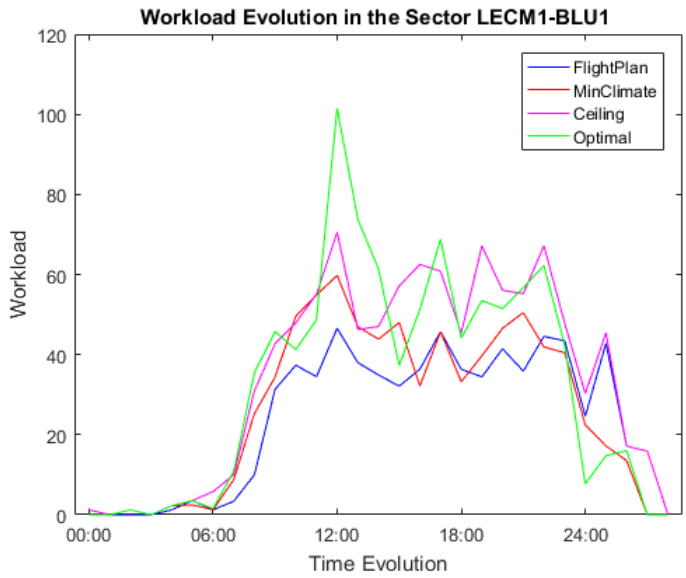


**Figure** 29: Workload evolution over LECM1-BLU1 sector

### 4.3.2 LECM2-TLU1 Sector

LECM2-TLU1 is a upper airspace devoted sector, whose limiting altitudes are 34500 to 46000 feet. Then, this sector will mainly register fights in cruise phase. The shape and location in the Spanish sectorization can be observed in the Figure 42 at Appendix.

According to the results in Table 10, it is the *Minimum Climate Impact* case that registered the least number of movement because some of the aircraft fly below the sector. Nevertheless, the lowest conflict value corresponds to *Flight Plan* case. This is an expected result as those trajectories are generated with ATFM regulations.

In Figure 30, the only case study respecting the maximum capacity limit is the *Minimum Climate Impact* case. However, it has so many conflicts that the workload obtained is higher than in *Flight Plan*, see Figure 32.

It has to be mentioned that the *Optimal Profile* is the case study that shows the worst performance in the sector LECM2-TLU1.

**Table** 10: Total number of conflict and movements along the simulation for LECM2-TLU1 sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 501 | 407 | 636 | 653 |
| Total nº Conflicts | 22 | 129 | 190 | 144 |

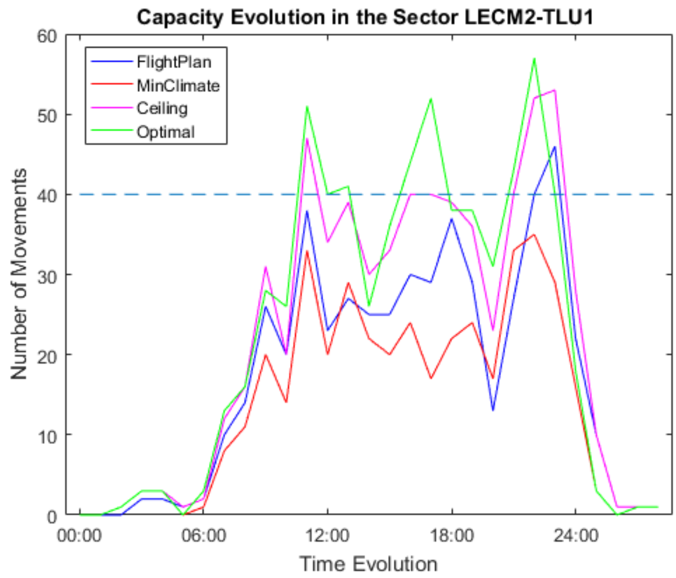


Figure 30: Sector Capacity evolution over the LECM2-TLU1 sector

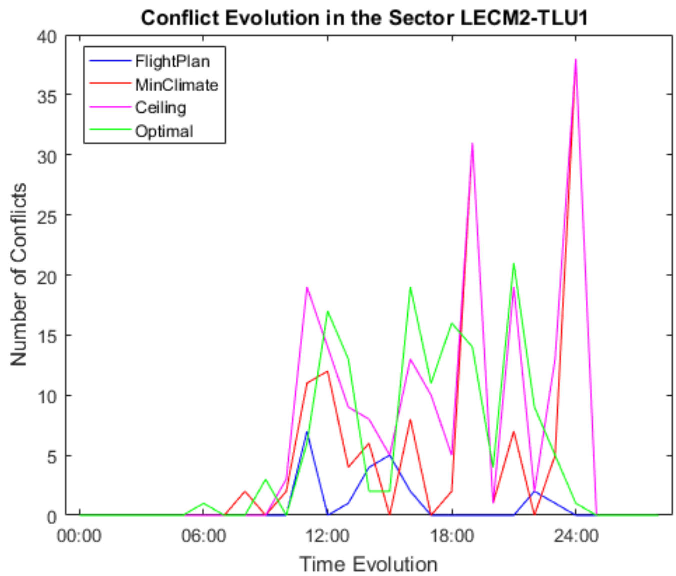


Figure 31: Conflict evolution over the LECM2-TLU1 sector

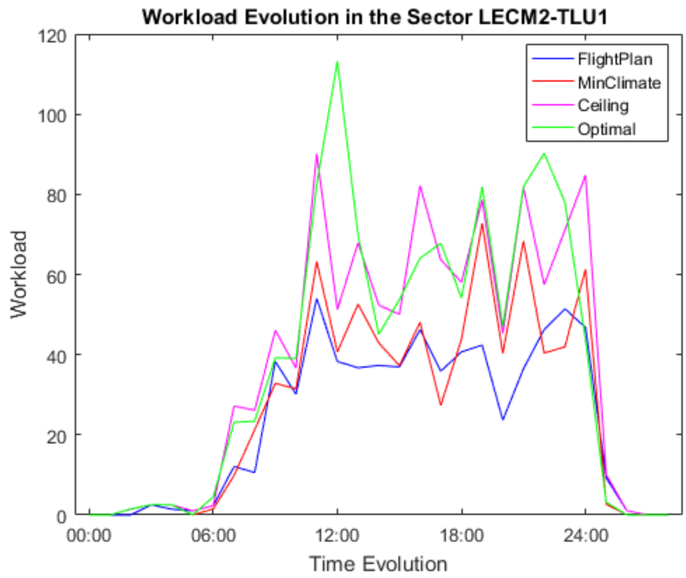


**Figure** 32: Workload evolution over LECM2-TLU1 sector

### 4.3.3 LEMDN-DEN1 Sector

LEMDN-DEN1 is a lower airspace devoted sector, whose limiting altitudes are 0 to 16000 feet. Then, it will mainly register flights in climb, approach and descend phases. Indeed, it corresponds to a sector in the vicinity of Adolfo Suarez-Madrid-Barajas airport. The shape and location in the Spanish sectorization can be observed in the Figure 41 at Appendix.

In Table 11, it is shown that all the cases have a similar aircraft movement number. This occurs because the climb and decent phases were designed in the same way for all case studies except from the *Optimal Profile* case. Moreover, It is interested to observe that the *Optimal Profile* detected the lowest number of conflicts. Instead, *Flight Plan* case registered the highest number of conflicts, even though its trajectories were generated with ATFM regulations.

Figures 33, 34 and 35 display the instantaneous capacity, conflicts and workload for the whole simulation. As it can be observed, both capacity and workload follow similar behaviours, while the conflict differ from each case study, just as commented before.

**Table** 11: Total number of conflict and movements along the simulation for LEMDN-DEN1 sector

| Case Study | Flight Plan | Min.Climate Impact | Aircraft Ceiling | Optimal |
|---|---|---|---|---|
| Total nº Movements | 473 | 473 | 474 | 456 |
| Total nº Conflicts | 167 | 123 | 116 | 69 |

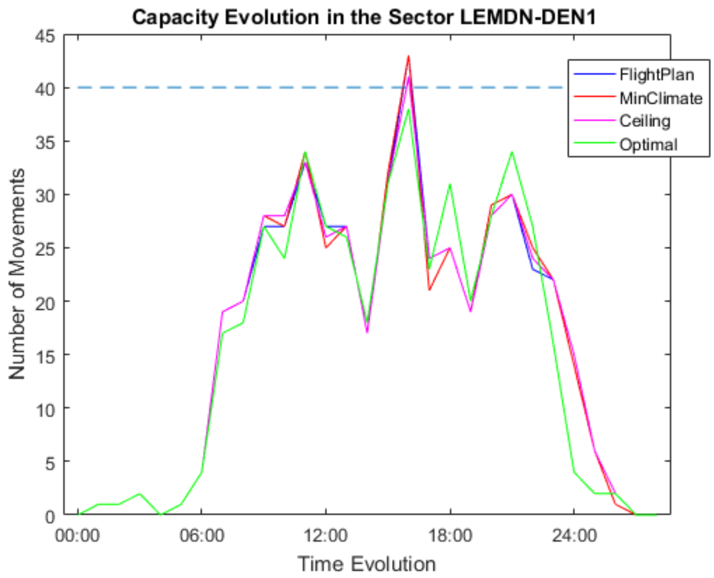


**Figure** 33: Sector Capacity evolution over the LEMDN-DEN1 sector

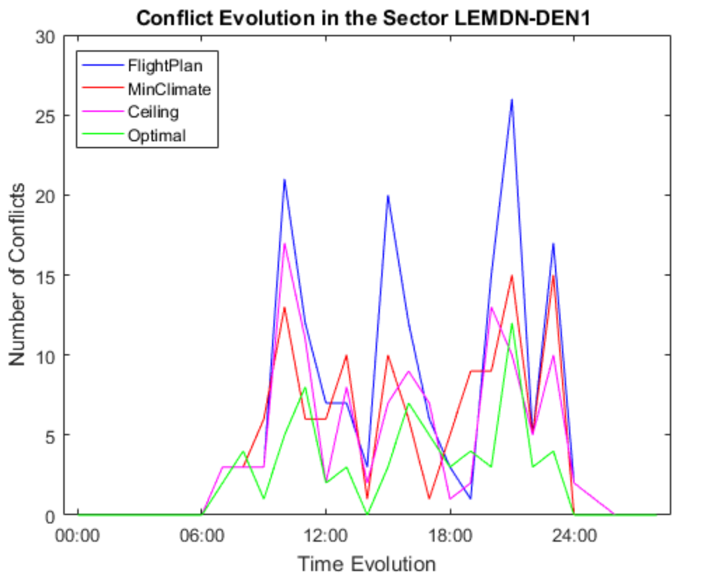


**Figure** 34: Conflict evolution over the LEMDN-DEN1 sector

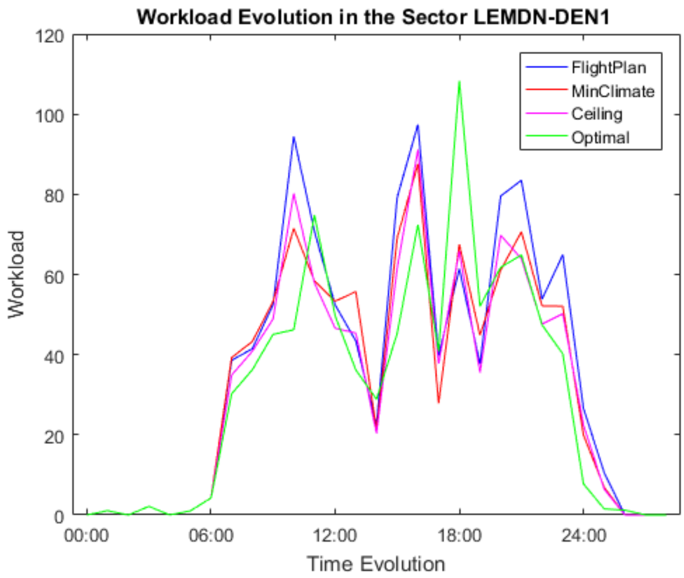


**Figure** 35: Workload evolution over LEMDN-DEN1 sector

## 4.4 2-D Sector Mapping

With the purpose of understanding in a more clear way the ATM performance of each case study, it was computed a temporal performance simulation of the entire air traffic scenario and it was represented in a 2-D map of the Spanish ATC sectors of the Iberic mainland. In order to shown the results obtained in this bachelor thesis, 2 different busy moments along the simulation where selected. The parameters chosen to compare the ATM performance are aircraft movement and number of conflict.

In Figure 36, it is shown the capacity mapping. It is not easy to determine a general conclusion, since depending on the trajectory implemented traffic congestions may locate in one sector or another. However, it can be observed that *Flight Plan* case is the least congested one, because it shows more green regions than the remaining case studies.

The Figure 37 represents conflict count mapping. As it was observed previously in the global data, *Aircraft Ceiling* is the case with more conflicts; see that has more sectors coloured up. On the other hand, *Flight Plan* case do not shown very conflictive regions as no magenta colours are displayed. Also, for this specific instant of time, *Minimum Climate Impact* display less conflicted regions than the other case studies.

On balance, all sectors show reasonable number of aircraft movement and conflicts.

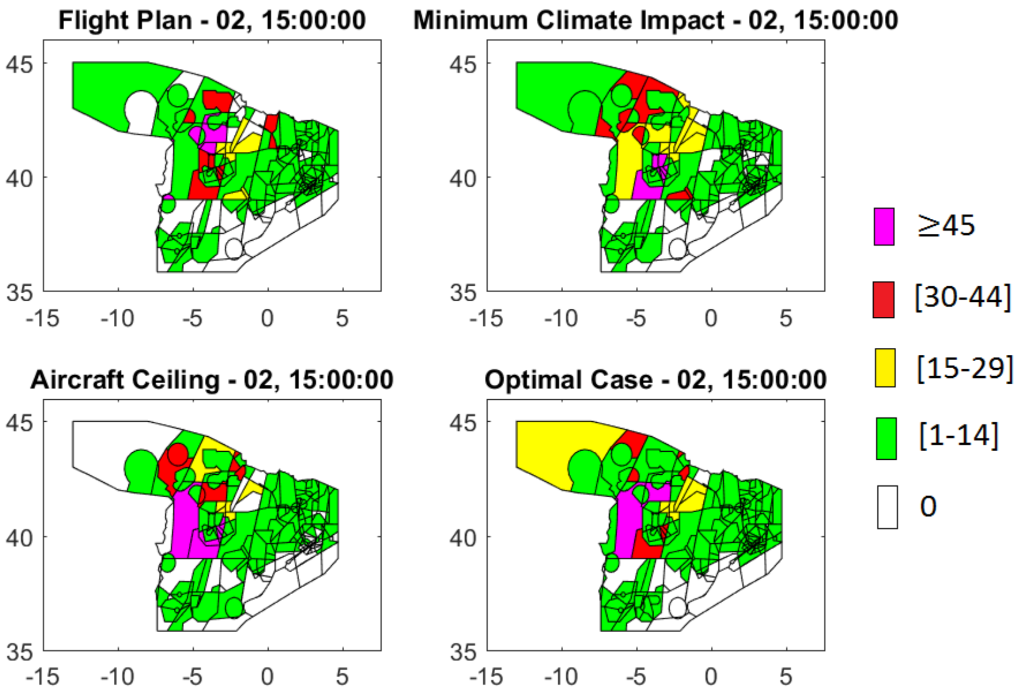


**Figure** 36: Instantaneous aircraft movement in 2-D mapping

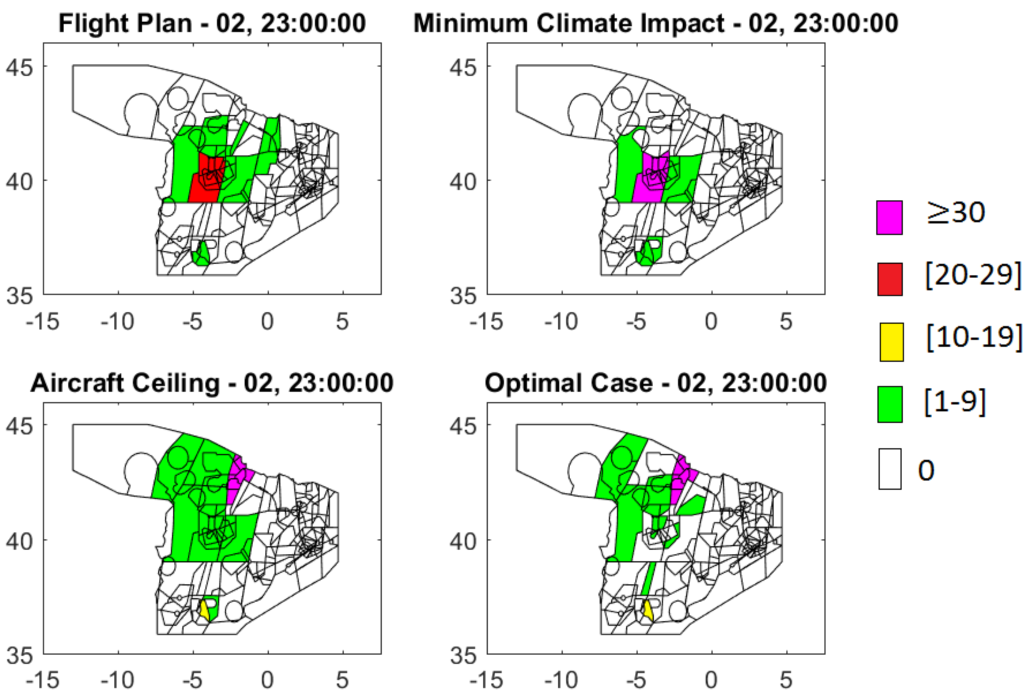


**Figure** 37: Instantaneous conflict count in 2-D mapping

## 4.5 Individual Aircraft Study

After performing global and localized analysis of the airspace sector, a more specific study was performed by choosing randomly an aircraft from the simulated air traffic flow.The identification number of the aircraft chosen is the 101. Then, for this aircraft three different parameters with respect of time were computed for all case studies: instantaneous position altitude, ground speed and fuel consumption. By performing individual checks, it is ensured that flights have been simulated properly or did suffer some type of incongruence.

Figure 38 shown the different vertical profiles for each case study. This type of graphs are very useful to understand the navigation of each trajectory. For this flight, there was a probability of contrail formation, thus, *Minimum Climate Impact* case selected a lower cruise FL. Also, it can be observed the continuous climb that characterises the *Optimal Profile* trajectories, maximizing the service ceiling.

In Figure 39, it is represented that ground speed of the aircraft at each instant of time. Note that the higher is flown, the lower cruise ground speed is. Hence, *Optimal Profile* case obtained the lowest ground speed, while *Minimum Climate Impact* case the highest one. These results will be directly related to the fuel consumption.

In Figure 40, it is appreciated clearly the benefit of setting *Optimal Profile* trajectory configuration in terms of fuel consumption. Indeed, fuel consumption is decreased respectably compared to *Aircraft Service Ceiling* case, which is the current less consuming possible trajectory. On the other hand, *Minimum Climate Impact* case is the one burning more fuel, although the difference with *Flight Plan* is not that big.

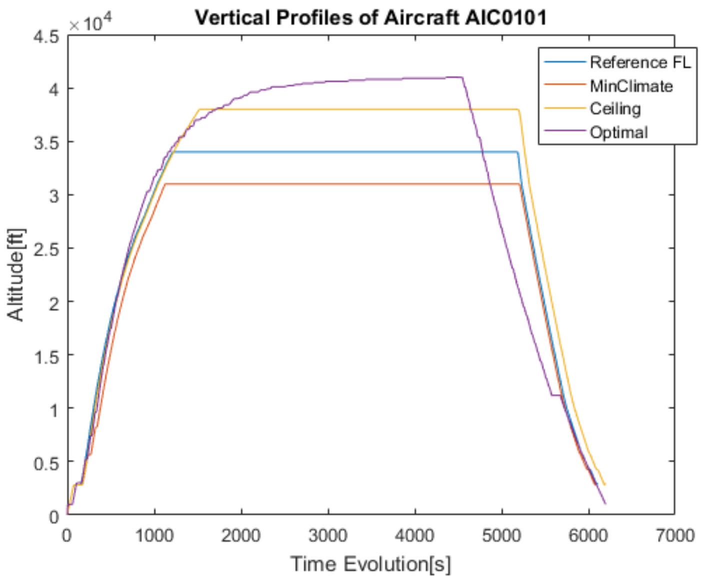


**Figure** 38: Comparison of the vertical profiles for AIC101 Aircraft

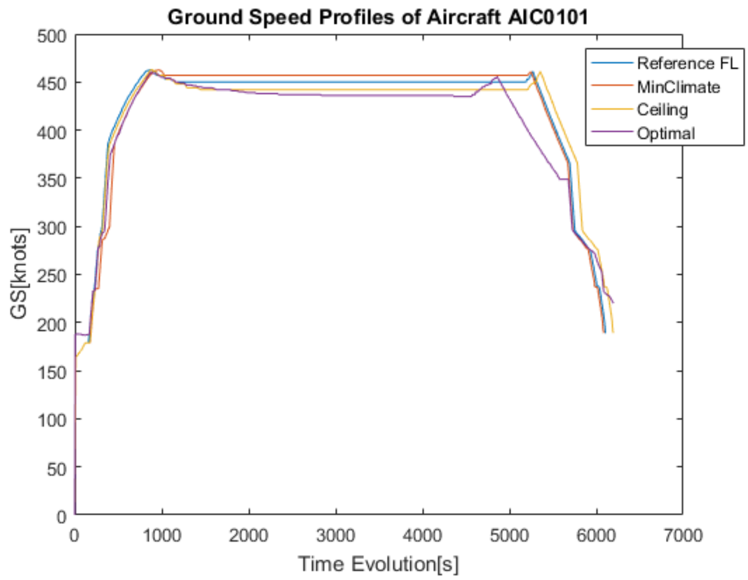


**Figure** 39: Comparison of the instantaneous ground speed for AIC101 Aircraft

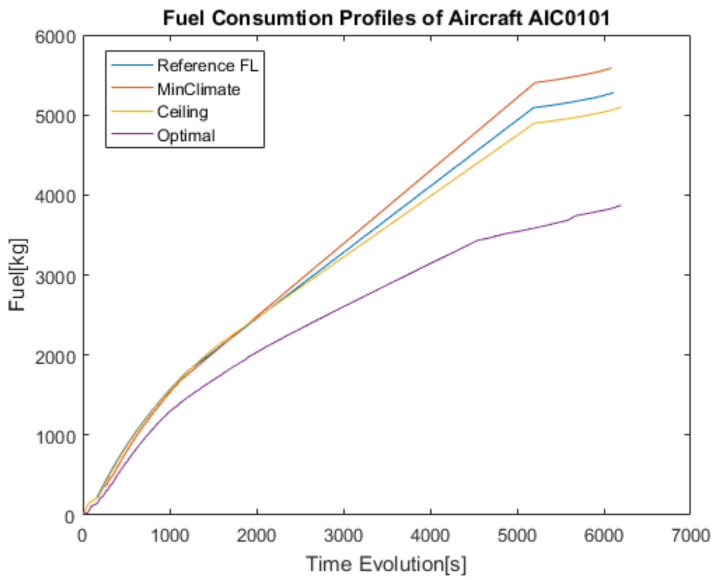


**Figure** 40: Comparison of the accumulated fuel consumption for AIC101 Aircraft

# 5 Conclusions and Future Work

In this section, there will be described the conclusions reached with the results obtained.

- Attending to the global ATM performance results obtained, studied cases show a detrimental result compared to the actual *Flight Plan* case. This conclusion was expected since the studied trajectories helping the reduction of environmental impact were not generated with ATFM regulations, hence, it is not awaiting to register worse performance. Nevertheless, no atypical behaviour was observed for both *Minimum Climate Impact* and *Optimal Profile* cases that would reject directly the possibility of implementing them into the actual air traffic scenario. In fact, all sectors showed reasonable number of aircraft movement and conflicts.

- In global terms, it has been validated that depending on the trajectory chosen, the fuel consumption of the flight will be higher or lower. *Minimum Climate Impact* consumes more fuel than any other configuration, whereas *Optimal Profile* is the one burning less fuel. Therefore, this conclusion could be interesting for airlines which seek for any possible cost reduction. Moreover, in a short future, in which international regulatory authorities apply a tax for contrail formation, airlines would be highly interested in flying as *Minimum Climate Impact* trajectory. In fact, it portrays the best scenario in monetary aspects.

- Looking closer to the duration of a flight, it is interesting to observe that *Minimum Climate Impact* trajectories reach their destination within the same minute time as actual trajectories. Therefore, actual schedules would not be strongly affected if this sort of trajectories would be implemented. A priori, airlines would not have to make big changes in their actual schedules. On the other hand, *Optimal Profile* arrives the destination 1 hour later compared to the mean *Flight Plan*, so it might not be very attractive for some airlines which try to provide passengers the fastest possible service.

- When working with ATM performance it is important to analyse globally air traffic, but also reduce the area of study. The reason for this is that, although globally achieved result may look upsetting, in smaller regions or sectors the performance of new designed trajectories might prove possible.

Next, there are going to be mentioned several aspects that should be improved and future steps to be followed with this project.

- Several inconsistencies were identified in this project, such as the rejection of a bunch of trajectories, aircraft movement counts at LE sector for *Minimum Climate Impact* case and incorrect generation of TAAM of some flight paths. Then, correcting these type of issues would be the first task to perform.

- The following step would be representing the case studies in the most realistic possible manner to the actual airspace, in other words, implement airspace restricted ares, limit the capacity of a concrete sector, apply the TAAM Conflict Resolutor tool and ATFM regulations. TAAM gives the user the possibility of implementing these characteristics.

- One of objectives of this bachelor thesis was to publish a paper with the results obtained in EIWAC 2017 conference. ENRI is a national laboratory leading research and development on air navigation systems, which currently is soliciting research and information papers concerning Air Traffic Management(ATM), Communication, Navigation and Surveillance(CNS) through the fifth ENRI International Workshop on ATM and CNS (EIWAC2017). On the 22nd of September of 2017 a paper was submitted into the EIWAC 2017 platform with the conclusions derived from this bachelor thesis. The authors of the paper are 4 members from the Aerospace department of Carlos III University, including myself, that have worked on this research project. Then, the next step will be attend the EIWAC 2017 conference in order to present and explain the work performed.

# 6 Project Budget

Lastly, the approximated budget of the project was computed. It is a interesting indicator of how much an ATM performance dissertation of a real air traffic scenario using a ATM simulator software can cost.

Table 12 shows the distribution of the project in terms of student labour. Considering the project as a work for technical engineer work, a salary of 20€per hours as been estimated. Regarding the usage of TAAM simulator, the university obtained an annual license of 5000€, which makes a 0.57€per hour cost. Finally, an approximated cost of electricity was computed because a whole room and a desktop computer was used at its full capacity every time TAAM simulator was used. Then, the room where TAAM is installed counts with 12 fluorescent bulbs and each one of them consumes 18 watts per hour approximately. Also, a desktop computer consumes a mean of 170 watts per hour. According to Iberdrola Company, the actual electricity bill is 0.18587 €/kwh. The time using "TAAM License" and "Electricity" corresponds to the sum of "TAAM Set-Up Time" and "Data Processing Time".

**Table** 12: Time distribution of the project labour

| Labour Type | Hours |
|---|---|
| Literature review | 30 |
| TAAM Set-up | 150 |
| Data Processing | 50 |
| Thesis Writing | 110 |
| Total | 340 |

**Table** 13: Calculation of the total cost of the project

| Type of Cost | €/h | Time[h] | Total[€] |
|---|---|---|---|
| Labour | 20 | 340 | 6800 |
| TAAM License | 0.57 | 200 | 114 |
| Electricity | 0.18587 | 200 | 446.1 |
| Total | - | - | 7360.1 |

All the values expressed in Table 13 have been corroborated by the supervisor of bachelor thesis, Javier Garcia-Heras Carretero. Hence, in order to perform the analysis of a low air traffic flow with TAAM simulator costs about 7360€. Note, that the main contribution comes from the worker labour.

# Acknowledgement

First of all, I would like to show my gratitude to Manuel Fernando Soler Arnedo for offering me the opportunity of joining this ATM research team. Also, I would like to shown enormous gratitude to my supervisor Javier Garcia-Heras Carretero for his infinite help and patience during the last months of work. I would like to remark that this thesis would not be the same if it was not for his help.

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Lastly, I want to thank my family for giving the opportunity and encourage me to study. To be precise, I want to thank my parents and brother. Thank you so much for inculcating me the values that now define me as a human being.

# A

**Figure** 41: Location of LECM1-BLU1 sector

**Figure** 42: Location of LECM2-TLU1 sector

**Figure** 43: Location of LEMDN-DEN1 sector

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