Eco-Efficient Aircraft by Operations

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September 2014

Abstract

The incessant growth in Aviation along with the increase of the warming in Earth's surface and the atmospheric pollution, leads to new developments in the field of operations practices. These developments represent a reduction in the fuel consumption and in the aircraft emissions, while improving the safety parameter. The thesis has for objective to analyse the optimized flight trajectories of two new operations concepts, CDO and FRA, in order to prove a reduction in the fuel consumption and aircraft pollutant emissions as well as the perceived aircraft noise. To calculate the quantity of aircraft pollutant emissions produced in such operations, AMEIII methodology is used. To measure the aircraft noise produced in CDO procedure, a proposal method is presented, tested and validated. The results obtained show a diminution in the pollutant emissions and the noise. An investigation in how the change in atmospheric parameters affects the total amount of the pollutant emissions is carried out. In addition to this, the environmental impact and the cost savings with the implementation of these operations are analysed in accordance to the annual flight movements. The new operations practices show an enhancement in optimized airspace usage, while safety is significantly enlarged and the aviation emissions are reduced.

Keywords: Pollutant emissions, Noise, Operations, Environmental impact.

1. Introduction

With the extensive growth of air traffic over the past decades, the concern of the International Aviation Community to reduce aircraft emissions has gained significantly importance and attention. This is, in the sector of the aviation industry, mainly in terms of diminishing the environmental impact by decreasing aviation emissions. As a matter of fact, the aviation is considered to be the fastest growing sector, when compared to the other sectors that are also producing greenhouse gases (GHG). As reference [1] states, the air traffic is estimated to grow with an average annual rate of 5 to 6 %. With this, the aviation sector plays an important role in terms of promoting new technologies and sustainable practices along with assurance of safety.

1.1. Motivation

According to the European Commission the global surface temperature of the earth increased of 0.6 °C during the 20th century, and it is estimated to increase between 1.8 and 5.8 °C until the year of 2100. The continuous warming of the Earth's surface, due to more accumulated radiative forcing in the atmosphere will have several climate and social impacts, as it stimulates fewer cold days, more often heavier rainfall, summer droughts, glacier melting, rising of the sea level and more intensive storms. As Intergovernmental Panel on Climate Change (IPCC) reported, the aircraft emissions were responsible in 1992 for about 3.5% of the total accumulated anthropogenic radiative forcing in the atmosphere, and it may increase to 5.0% by 2050.

With the present scenario, the aviation industry has not only been promoting strategies to reduce their emissions, but also has been developing a more safe and optimized aircraft and more efficient and safe use of the airspace. The strategies to reduce aviation emissions include a range of options in different areas, which are indicated in the following:

- Aircraft and Engine Technology;
- Fuel Technology;
- Operational Practices;
- Regulatory and economic measures;

This present work is concerned with the area of Operational Practices, using two new optimized operation concepts, Continuous Descent Operation (CDO) and Free Route Airspace (FRA). These new concepts not only represent lower fuel burn and thus lower costs, but also a significant reduction in aircraft emissions, as well as an optimization of the

usage of the airspace. The feasibility of the operational changes must take into account the most dominant considerations in the aviation industry, being safety, environmental impact and costs parameters.

The aircraft emissions herewith analysed are respected to the pollutant species NO_x, UHC and CO, as well as the noise produced. The major contribution of this work is to prove the efficiency in reducing the fuel and thus, the pollutant emissions while safety is increasing, when these operations are performed. As certification and regulation on these emissions are still limited below to 3000 ft, this work also gives a global idea about the amount of the pollutant species produced by the aircraft at such phases. In addition to that, noise emissions at descent phase will be also analysed, since CDO also benefits from reducing the aircraft noise emissions.

2. Background

2.1. Aircraft Engine Emissions

Aviation is a significant source of pollution worldwide, as the aircraft engines use combustion principles to produce the required power to fly while releasing emissions into the atmosphere. As the combustion process of an aircraft engine is not ideal, such emissions comprise the greenhouse gases carbon dioxide (CO_2) and water vapour (H_2O) and the pollutant species nitrogen oxides (NO_x :comprises NO and NO_2), carbon monoxide (CO), as well as a variety of unburned hydrocarbons (UHC, shorted here to HC), sulphur oxides, soot and other particles.

The aircraft emissions have more environmental impact at higher altitudes, whereby they induce directly changes in the amount of radiative forcing in the atmosphere. At ground level, these emissions have effects on local air quality in the airport vicinity. The greenhouse gases CO_2 and H_2O are directly produced by the combustion of the engine, and therefore, they can only be reduced by increasing the efficiency of the fuel consumption. It is more complex to reduce the produced amount of other exhaust gases, since the combustion process is not ideal. The amount of these depends strongly on the specific engine, its power setting and ambient engine inlet conditions.

Aviation emissions, when compared to the other major anthropogenic emission sources, are the only that are emitted directly into the Upper Troposphere Lower Stratosphere (UTLS), in which pollutants have a longer lifetime than close to the Earth's surface. The CO_2 and H_2O and the NO_x species produced by the aircraft are the major concern in terms of environmental impact. Although, the most gases contribute to the warming of the atmosphere by increasing the accumulated positive radiative forcing in atmosphere, as figure 1 shows, these three species have major effect. Along with this, aircraft emissions also induce formation of contrails, cirrus clouds and smog.

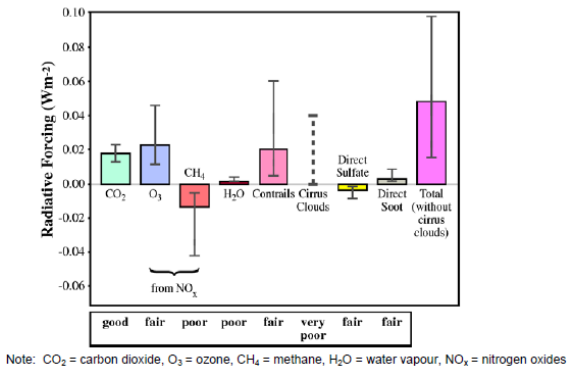


Figure 1: Effect of historic aviation emissions on the warming capacity [2]

2.1.1. Certification

In order to control the local air quality in the vicinity of big airports, ICAO imposes a standardized landing and take-off (LTO) cycle. The LTO cycle is referred to the aircraft movements from the ground up to 3000 ft. All engines from aircraft manufactures must be tested on the gaseous emissions of NOx, HC, CO and soot at specified thrust settings, shown in table 1, and they must be reported in a form of the rate of fuel flow and emission index to the ICAO. The ICAO Engine Exhaust Emissions Databank provides all these information.

Operating mode	Thrust Setting	Time (min)
Take-off	100 % F_∞	0.7
Climb	85 % F_∞	2.2
Approach	30 % F_∞	4.0
Taxi/idle	7% F_∞	26.0

Table 1: ICAO operating rates of the LTO cyle

2.2. Noise

The sound produced from a certain source propagates trough the air in space and time, as a progressive wave. For the sound of an aircraft, the produced wave propagates as a spherical wave front and the aircraft sound source can be considered as a punctual source in a free field. Noise is referred to as unpleasant sound and is a subjective phenomenon. According to [3], the noise produced by the aircraft is a combination of several isolated sources. The major aircraft noise comes from the engines, and the second biggest source is the airframe, due to the airflow around the aircraft.

The measurement of the aircraft noise during a flyover is executed in a ground receiver under the flight path. At observer position the noise is usually measured in a metrics of SPL (Sound Pressure Level, in dB), in combination with a time history. As the aircraft is a moving sound source, its sound radiation is not constant but is variable with the frequency and intensity of the sound. Therefore, in order to account this fact in the noise measurement of a flyover, directivity and attenuation effects of the air must be also considered.

The sound is absorbed by the air with rising the distance to the source. Inverse-distance law states that in the far field, the amplitude of the sound pressure is decreased by the inverse distance to the source, by a factor $1/r$. According to [4], the inverse-distance law states that the reduction in sound pressure level due to spherical divergence is equal to 6 dB for each doubling of the distance to the source. However, this law dos not consider directivity and reflective surfaces, as well as barriers between the source and the point of the measurement. Using a reference distance of $r_1 = 1m$ as the distance of the near field, inverse-distance law can be written as:

$$SPL(r_1) - SPL(r) = 20 \cdot logr \qquad \text{,r is in meters} \tag{1}$$

2.2.1. Certification

ICAO Annex 16 Volume I sets the background for aircraft noise certification. The database of the noise certification of an aircraft is available in [5]. According to [6], the noise certification is measured in terms of loudness or annoyance levels. For propeller driven light airplanes and helicopters the maximum sound exposure level (SEL) in dBA is used to certify the noise. For jet or propeller driven heavy airplanes or helicopters the effective perceived noise level (EPNL) in EPNdB is used. An aircraft when performing noise certification must execute a series of landing and take-off manoeuvres over three distinct measurement points, being, the approach point, the lateral point and flyover point.

2.3. Strategies to reduce aviation emissions by Operations

Two important strategies to reduce aircraft emissions in terms of operations, CDO and FRA, have been progressively implemented. These strategies represent merely optimized flight routes which were possible due to technological developments. On the one hand, the the navigation systems have been improved to be more. On the other hand, these strategies were also a response to the growing of the air traffic flow over the last decades, aiming at a more efficient air traffic control.

Continuous Descent Operation-CDO

The CDO is defined as: - *is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions*- [7, p. 3].

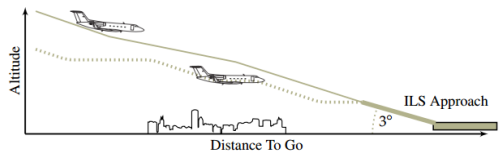


Figure 2: Altitude profile of a conventional descent (dashed) and a CDO descent (solid)

Figure 2 illustrates the difference between a CDO vs. Conventional Descent profile. As seen, in a conventional descent or non-CDO profile, the aircraft descends step-wise, with elements of level flight in-between. When performing a CDO profile, the aircraft remains at higher altitudes throughout a longer period of time where it operates at lower engine thrust. These elements result in a reduction in fuel use, emissions and noise. The ideal CDO profile should start at the top of descent point (TOD) and continue through to the final approach fix (FAF)/final approach point (FAP). Traffic sequencing could be achieved by small speed interventions during the cruise or early phases of descent, thereby minimizing sequencing manoeuvres at lower altitudes. The most economical descent would be a continuous descent flown at idle conditions until a point where flaps and landing gear are deployed. The idle condition is standardized in table 1. According to [8] the advantages offered by the CDO profile can be summarized as::

- more efficient use of the arrival airspace;
- more consistent flight paths;
- reduction in both pilot and controller workload;
- reduction in the number of required radio transmissions;
- cost savings and environmental benefits due to reduced fuel burn;
- reducing the incidence of controlled flight into terrain (CFIT);
- operations authorized where noise limitations would result in operations being curtailed or restricted.

As shown in the figure 2, conventional routes are more complex in terms of manoeuvring the aircraft, as they may have several flight level segments, with less stability resulting in more power needed to control the aircraft and thus more flight time. Therefore, CDO procedure is an optimized path which reduces the complexity and complications of the non-CDO path while increasing safety. In agreement with EUROCONTROL, the implementation of CDO would represent:

- A noise reduction up to 5 decibels [dB],
- NO_x reduction up to 30% and CO up to 20%,
- Fuel saving up to 500 lbs per operation,
- A noise impact concentrated in narrow corridors,
- Reduction in total flight time,
- Less engine thrust resulting in an increase in the turbine live cycle
- A reduction of overall flight time to a minimum while cruise altitude is prolonged

To perform a CDO, an optimum vertical path angle must be achieved. This depends on the type of aircraft and its weight as well as meteorological conditions such as wind, air temperature and pressure, icing conditions and other dynamics considerations. The supported systems, such vertical navigation (VNAV) and flight management system (FMS), are not mandatory to execute a CDO. Additionally, in order to accurately calculate the flight descent path it is helpful knowing the flight distance to the runway and the level above the runway from which CDO is to be initiated. However, the exact distance or time to be flown until landing is not always precisely known. The Performance Based Navigation (PNB) integrates RNAV and RNP systems, combined with a framework for Navigation Application, and is nowadays the most accurate navigation system, which allows to define performance requirements resulting from ATS and Instrument Flight Procedures (IFP).

As for IFP in a descent operation the pilot can use two types of instrumentation rules, Instrument Flight Rules (IFR) or Visual Flight Rules(VFR). Depending on weather conditions the pilot must opt from one of these two types. IFR uses on-board navigation instruments such as RNP and GPS, and the route is performed exclusively with this information regardless visibility. In contrary to this, the VFR navigates with reference to outside visual cues in order to maintain the aircraft straight and adjust the level and prevent collisions. For this reason the latter is only allowed when minimum visibility conditions are available, which are defined by FAR Part 91.155. It is never allowed to use the VFR system when flying above the cloud ceiling or crossing through the clouds. Obviously IFR is safer than VFR, and therefore commercial airline pilots must always navigate with IFR, weather having clear visibility or not. VFR is often used for smaller aircraft. When the aircraft reaches the FAF/FAP point, the Instrument Landing System (ILS) must be used.

According to [9], CDO procedures can be currently designed by two different methods. These are founded on lateral path fixed routes, identified as "closed path" and "open path" designs. The two methodologies originate from the need to provide different ways to assist the flight distance to the runway threshold.

A successful implementation of CDO, would require a full collaboration between all stakeholders. As mentioned before, CDO enables a more efficient fuel performance as well as lower environmental impact, and therefore most of the airlines and airports in Europe execute CDO. The implementation of CDO has been executed gradually since 2004. Each airport and airspace may integrate CDO according to its capacity and terrain influence as well the environmental impact on the surroundings.

Figure 3 gives an example of a successful implementation of the CDO. Taking a look at the difference between the conventional and the CDO procedure it is notable, that the CDO procedure compacts traffic in a line space. Full implementation of CDO creates a tiny path flux, in which the aircraft operates at lower thrust engine, resulting in lower fuel consumption and subsequent emissions. Nowadays conventional arrivals in Europe are only used, if there are flight level restriction due the traffic or military conditions, since conventional arrival is slower than the CDO and may delay the descent.

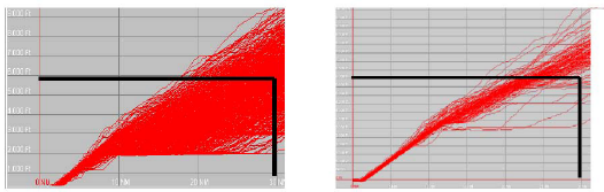


Figure 3: Descent trajectories before CDO (right) and after CDO (left) [9]

To sum up,CDO is an optimized descent operation, in which allows to reduce the fuel consumption, and pollutant emissions as well as the noise. At the same time, safety is widely increased. In addition to that, airspace capacity is also increased, since the trajectories are compress to one flux path, with less time and engine thrust.

2.3.1. Free Route Airspace -FRA

FRA can be defined as: *-a specific airspace within users shall freely plan their routes between an entry point and an exit point without reference the ATS route network. In this airspace flights will remains subject to air traffic control.* [10, p. 1]

The main concept of FRA is to fly safely unrestricted through the airspace in contrary to a conventional route which is fixed and constrained by waypoints. At same time, the aim of the FRA is to optimize the use of the entire airspace while maintaining safety. The figure 4 shows both concepts.

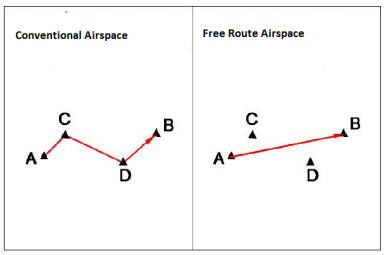


Figure 4: Scheme of the FRA concept

Along the development of the navigation sensors systems, this concept has been settled as a response to the need to improve airspace capacity due to the huge traffic growth. In addition to that, international community regulators urges more environmentally friendly use of the airspace, i.e., reducing fuel and emissions. Therefore ATS route network has become inefficient to match these requirements. According to [10] the goals of FRA are:

- Increase airspace capacity;
- Enhance flexibility;
- Financial and operational benefits to the airspace users;
- Optimize the use of existing and foreseen airborne systems;

Free Route integrates PNB navigation system with vertical and horizontal limits. Below these limits ATS route network is used. With the nonexistence of any fixed route network from FRA, the associated crossing and congestion points also disappear. In their place will be a greater number of random crossing points associated with individual flight profiles rather than route alignment. In terms of monitoring, this represents that the safety issue can be diminished. Since safety is depending on the controller and its workload. In order to counter this, the Central Flow Management Unit (CFMU) service has been improved, which allows to process free route flight plans and to distinguish between different times of day in the event that FRA would be implemented only for part of the day.

The Free Route project was developed by EUROCONTROL in 2001 and was first implemented in Sweden in 2007. The project has been developed to face the need to improve the airspace as the air traffic grows rapidly. The airspace is segregated by Sates and/or countries and limited by FIR boundaries. The EUROCONTROL aims to organise the entire European airspace in blocks instead of these boundaries, in which intends to implement full Free Route system. Although, the implementation requires full collaborative of the FIR States, as a primary step it is to meet the future capacity and safety needs through legislation.

In 2009 FRA was implemented in the Portuguese airspace for flight levels above FL245, in Lisboa FIR (named as FRAL, Free Route Airspace Lisboa) and in Santa Maria FIR. An example is shown in the figure 5, which compares the same route before and after launching the FRAL:

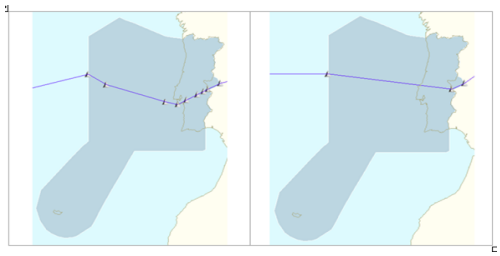


Figure 5: Example of a flight planning from Madrid to Boston before (left) and after (right) FRAL implementation [11]

According to [11] after one year of operation FRAL project was enabled to:

- reduce 1300000 NM;
- save in fuel 8783 Tones;
- save over 12 million Euro;
- spare 27 000 Tones CO_2;
- save with Santa Maria Oceanic intersection frowns in 12500NM/month;

The FRAL next aims are to extent the vertical limitation to above FL195, a new sector configuration, and improvement of Cross-Border (DCT) with Santa Maria FIR. In Santa Maria FIR is often authorized to execute an optimization of lateral profile when weather conditions are more favourable, and as well as is authorized cruise climb technique, everytime is possible. In addition to that, most pilots in transatlantic routes try to go in airways where the wind is strongly favourable.

According to [12], in the year 2009 were performed 48 test flights in Santa Maria FIR were performed and as result these test enable:

- a fuel saving between 29 and 200 kg;
- CO2 reduction between 90 and 650 kg;

3. Emission Estimation Methods

The methodologies used for the calculation of the CO, HC and $N0_x$ emissions and the noise are proposed for the flight phases analysed, and therefore simplified according to the available input data. Nevertheless, they intend to accomplish proximity with some software used in Aviation Industry.

3.1. The CO, HC, NO_x calculation method

In order to quantify the amount of aircraft emissions produced throughout any flight phase, the Boeing Aircraft Company has established a theoretical algorithm called Boeing 2 method (BM2) to measure CO, HC, NO_x emissions depending on the type of the aircraft and its performance as well as the atmospheric conditions. This method is commonly used in Aviation sector. The EUROCONTROL has likewise developed a similar method called Advanced Emission Model III (AEMIII), which uses the BM2 algorithms with slight modification. The AEMIII adjust values from ICAO emission database regarding changes in temperature, pressure and relative humidity at altitude. The fuel flow used depends on the altitude level, the AMEIII uses the ICAO fuel flow when below 3000ft and BADA fuel flow when above it. This method is detailed described in [13].

As a difficulty encountered when constructed the AMEIII method, is the lack of independent reference values as well as access to proper data. Thus, the previous method was simplified according to the available data.

First, for a given CDO profile, it is divided by the number of segments in the flight phases, and each segment it is divided in 5 points. In the following the simplifications assumed are listed:

- The ICAO database of the approach phase is used as reference values of REICO, REIHC and REINOx, since at this phase the throttle setting is assumed to be at an average of 30%.
- The ambient pressure and temperature are assumed as International Standard Atmosphere (ISA) which depends only on the altitude.
- The W_f, is assumed as constant with a value of 30% of the maximum throttle setting of the aircraft. The Mach number, M.
- The relative humidity(ϕ) is assumed to be constant during the entire descent profile, it is computed assuming several day cases: 1- 0%, 2- 45%, 3-63%, 4-85%, 5-90% and 6-100%.
- The time of each segment is obtained as linear decrease in accordance with the maximum speed restriction for each flight level.

3.2. The Noise Calculation Method

Due to the lack of significant information and access to some accurate software used in Aviation Industry, this method is proposed accordingly for the purpose of this project. Which is to compare the CDO operations with the respective conventional descent procedure.The input aircraft data is given by the ANP database, which offers a set of tables depending on each type of aircraft. For each aircraft the NPD relationships are given, regarding the operation mode and the installed thrust, as well as the noise level emitted by the 24 1/3-octave frequencies, depending on the operation mode.

SETP 1: import the 24 1/3-octave frequency spectral classes from ANP database.

STEP 2:The reference spectrum is corrected to the distance of 1m from the source, by removing the attenuation factor SAE AIR-1845, $\alpha_{n,ref}$, where n is the frequency band:

$$L_{n,source}(d_{1m}) = L_{ref}(d_{ref}) + \alpha_{n,ref} * d_{ref} \quad (2)$$

STEP 3:Calculation of the sound level in dB for a given distance, using the inverse distance law with directivity and atmospheric SAE AIR-1845 attenuation factors. The inverse distance law is given by:

$$L_{n,i}(d_i) = L_{n,source}(d_{1m}) - 20\log(d_i/d_{ref}) \quad (3)$$

$$-\alpha_{n,ref} \cdot d_i + DI(\theta) \quad (4)$$

$$DI(\theta) = L_{n,i}(d_i) - L_{n,avg} \quad (5)$$

STEP 4: Each point of the considered flight path is linked to a L_n of each 1/3 octave frequencies. Thus, for each point the overall noy and the corresponding PNL (L_{PN}) are calculated by:

$$N = n_{max} + 0.15 \cdot \left[\sum n - n_{max}\right] \quad (6)$$

$$L_{PN} = 40 + \log_2 N \qquad \text{in PNdB} \quad (7)$$

STEP 5:Integration of the PNL over time to obtain EPNL (L_{EPN}):

$$L_{EPN} = 10\log\left[\frac{1}{T_{10}}\sum_i 10^{L_{PN}(t)/10} \cdot \Delta t\right] \text{in EPNdB} \quad (8)$$

ID	Aircraft	Engine
1	Boeing 747-400	PW 4062
2	Airbus A321	CFM56-5B1
3	CRJ-700	GE CF34-8C5A1

Table 2: Aircraft typical classes

4. Construction of the Fight Profiles

Table 2 classifies some typical civil aircraft, which will be further used to quantify the aircraft emissions during specific operations. Each aircraft was chosen to be representative from the class.

Concerning, the CDO operations, the profiles were chosen respected to the Lisbon and Faro airport. Table 3 indicates tha runway (RWY) direction and the name of the group, which is comprised by the two types of CDO with a descent angle of 3° or 3.3° and the respective conventional profile. In Portuguese Airports there are only four CDO published in a form od STAR.

LPPT airport	RWY	LPFR airport	RWY
Via UNPOT	03	Via SOTEX	10
Via IMBOM	03	Via ODEMI	28

Table 3: Name of the CDO-STAR documents published in Portuguese airports

The CO, HC, NO_x calculation method uses the entire profiles of each route, and the noise calculation method only uses the last segment close to the FAP/FAR point, i.e, prior to the LTO cycle.

Respecting the FRA operations, four routes were considered. In each route several profiles were constructed in accordance with the navigation system. Table 4 enumerates the routes as well as the corresponding navigation system used. The GPS is concerned to the direct route and thus, the FRA.

Route	Navigation
Porto-Lisbon	VOR RNAV GPS
Paris-Lisbon	VOR from west VOR from south-east RNAV from west RNAV from south-east GPS
Lisbon-New York	TAC RNAV GPS
Lisbon-Fortaleza	RNAV GPS

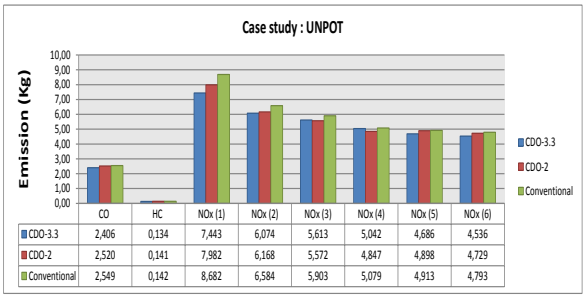
Table 4: En-route profiles with the type of navigation system

5. Results

In order to discuss the results obtained from the $CO - HC - NO_x$ method for the different profiles, the results had to be generated under the same input base. In addition to that, the results of the total amount of the pollutant emissions may not accurately represent the reality, due to the used simplifications in the method.

5.1. CDO Results

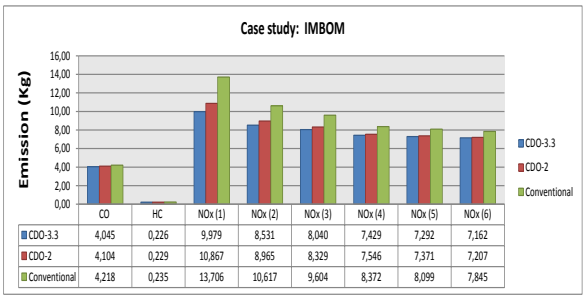
Case Study: CDO via UNPOT



	CO	HC	NOx (1)	NOx (2)	NOx (3)	NOx (4)	NOx (5)	NOx (6)
CDO-3.3	2,406	0,134	7,443	6,074	5,613	5,042	4,686	4,536
CDO-2	2,520	0,141	7,982	6,168	5,572	4,847	4,898	4,729
Conventional	2,549	0,142	8,682	6,584	5,903	5,079	4,913	4,793

Figure 6: Case UNPOT profile with category 2

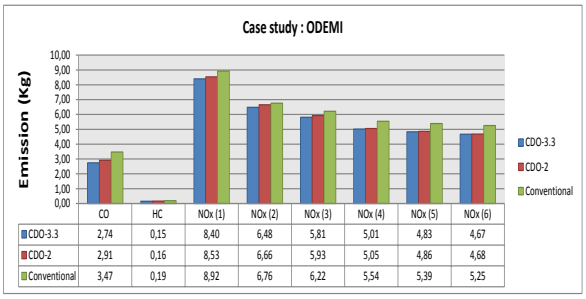
Case Study: CDO via IMBOM



	CO	HC	NOx (1)	NOx (2)	NOx (3)	NOx (4)	NOx (5)	NOx (6)
CDO-3.3	4,045	0,226	9,979	8,531	8,040	7,429	7,292	7,162
CDO-2	4,104	0,229	10,867	8,965	8,329	7,546	7,371	7,207
Conventional	4,218	0,235	13,706	10,617	9,604	8,372	8,099	7,845

Figure 7: Case IMBOM profile with category 2

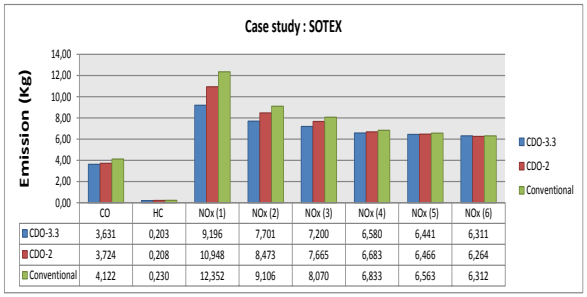
Case study: CDO via ODEMI



	CO	HC	NOx (1)	NOx (2)	NOx (3)	NOx (4)	NOx (5)	NOx (6)
CDO-3.3	2,74	0,15	8,40	6,48	5,81	5,01	4,83	4,67
CDO-2	2,91	0,16	8,53	6,66	5,93	5,05	4,86	4,68
Conventional	3,47	0,19	8,92	6,76	6,22	5,54	5,39	5,25

Figure 8: Case ODEMI profile with category 2

Case Study: CDO via SOTEX



	CO	HC	NOx (1)	NOx (2)	NOx (3)	NOx (4)	NOx (5)	NOx (6)
CDO-3.3	3,631	0,203	9,196	7,701	7,200	6,580	6,441	6,311
CDO-2	3,724	0,208	10,948	8,473	7,665	6,683	6,466	6,264
Conventional	4,122	0,230	12,352	9,106	8,070	6,833	6,563	6,312

Figure 9: Case SOTEX profile with category 2

As can be obtained from the previous figures 6,7, 9 and 8, the NO_x emissions are the largest quantity produced, followed by the CO and HC. Comparing the conventional profile with the two types of CDO-profiles, the CO and HC emissions have the same percentage reduction between the route types. The reason for this is that both pollutant emissions depend only on the reference fuel flow and the REI, which is constant throughout the entire profile, as well as on temperature and pressure, which vary only with the altitude. When it comes to the NO_x emissions, the mass amount produced tends to be higher for lower relative humidity, which is in accordance what is stated in reference [14]

In general, the CDO-profile with a descent angle of 3.3° seems to be the profile which has the largest percentage in reduction of the total pollutant emissions. This was expected, due to the fact that it stays at higher altitudes throughout a longer time period. However, there are few cases where the CDO-profile with a descent angle of 2° has higher reductions regarding the NO_x emissions. The reason for this is the construction of the simulation program is not entirely accurate.

In order to investigate how the amount of the emissions are affected with change in ISA temperature and humidity a study was executed. The HC and CO Emission Index are not influenced by the humidity, thus they are increased of around 1.4% for each degree in temperature in °C. The NO_x emission index is decreased about a factor of around 0.7% for each degree in increasing temperature in °C and the change in humidity has a weak effect on the EI of NO_x.

The results in tables 5 and 6 are related to the noise measurement model proposed, where two different atmosphere noise absorption models are used, the SAE AIR-1845 (shorted to SAE) and ARP866A:10 °C/ 80% RH (shorted to ARP).

Points		SAE		ARP	
		EPNdB	Δ	EPNdB	Δ
P1	Conv	72.3		74.3	
	CDO	71.4	-0.9	73.5	-0.8
P2	Conv	72.3		74.3	
	CDO	69.9	-2.4	72.0	-2.3
P3	Conv	72.3		74.3	
	CDO	67.1	-5.2	69.4	-5.1

Table 5: EPNdB results for the points in the vicinity of Lisbon Airport

Points		SAE		ARP	
		EPNdB	Δ	EPNdB	Δ
P1	Conv	77.8		79.8	
	CDO	74.7	-3.1	76.7	-3.1
P2	Conv	77.6		79.7	
	CDO	71.8	-5.8	73.8	-5.9
P3	Conv	73.1		75.1	
	CDO	68.6	-4.5	70.7	-4.4

Table 6: EPNdB results for the points in the vicinity of Faro Airport

5.2. FRA results

Case study: Porto-Lisbon

Reduction	HC	CO	NOx
GPS-VOR	+ 4.8 %	+ 4.8 %	- 7 %
GPS-RNAV	+9.9 %	+ 9.9 %	-3 %

Table 7: Percentage reduction of the pollutant emissions of the routes between Porto to Lisbon

Case study:Paris- Lisbon

Reduction	HC	CO	NOx
GPS-VOR(N)	+ 4.1 %	+ 4.1 %	-1.9 %
GPS-RNAV(N)	+5.0 %	+ 5.0 %	-2.0 %
GPS-VOR(S)	-8.7 %	-8.7 %	-10.1 %
GPS-RNAV(S)	-13.3 %	-13.3 %	-14.5 %

Table 8: Percentage reduction of the pollutant emissions of the routes between Paris to Lisbon

Case study: Lisbon-New York

Reduction	HC	CO	NOx
GPS-TAC	-43.1 %	-43.1 %	-44.1 %
GPS-RNAV	-24.5 %	-24.5 %	-26.3 %

Table 9: Percentage reduction of the pollutant emissions of the routes between Lisbon to New York

Case study: Lisbon-Fortaleza

Reduction	HC	CO	NOx
GPS-RNAV	-2.9 %	-2.9 %	-2.6 %

Table 10: Percentage reduction of the pollutant emissions of the routes between Lisbon to Fortaleza

In general the direct route is the most efficient route. It requires less fuel, time and operates on shorter distance, which is resulting in lower pollutant emissions. Besides this, is has less manoeuvres, as it does not have to cross throughout the VOR points and/or the way-points, representing safer operations.

For the short-range and for cases in medium-range, the efficiency of the GPS route is not in accordance with the expected. The route were estimated in flight planner tool from the Flight Simulator (FSx), and therefore the performance data is very similar. In addition to that, the FSx does not specify the instantaneous fuel burn, but instead the average value of the fuel burn for each considered segment.

However, it can be indicated that in terms of manoeuvring safely the aircraft, the direct route appears to be better, since it has less manoeuvres, and thus is considered the most efficient route.

5.3. Environmental Impact and Cost Analysis

In order to investigate the environmental impact of the operation practices described in the previous, firstly information on the movements during each day is required. Furthermore, for the present study, more detailed information on the type of route that each aircraft executes is also required. Since this sort of information is usually not available, a simplification approach had to be chosen. According to ANA annual report of 2011, the Portuguese airports connect with a total of 150 destinations worldwide. This report contains large significant information on the annual movements of 2011 of all Portuguese civil airports controlled by the ANA.

5.3.1. CDO Impact Investigation

The pollutant emissions are estimated according with the results obtained for each individual CDO operation. In addition to that, as the NO_x-emissions are depending on the relative humidity, 0% relative humidity case was used.

Season	Fuel (tonnes)	Time (min e+3)	NO_x (tonnes)	CO (tonnes)	HC (kg)
Winter	1 471	79	35.3	1.6	91.5
Summer	1 837	99	44.1	2.1	114.2

Table 11: Reduced fuel, time and pollutant emissions for CDO in Lisbon

Season	Fuel (tonnes)	Time (min)	NO_x (tonnes)	CO (tonnes)	HC (kg)
Winter	40.7	2208	1.1	1.5	86.6
Summer	119.5	6473	3.3	4.5	253.9

Table 12: Reduced fuel time and pollutant emissions for CDO in Faro

As the tables 11 and 12 indicates, the emitted species are highly reduced when considering a long period of time. Logically, this amount of reduction comes along with benefits for the ambient. In addition to that, these results are very relevant, as the air traffic is growing rapidly, since today's efforts are made in order to reduce the aviation emissions.

5.3.2. FRA impact investigation

Route	Fuel (tonnes)	Time (hours)	NO_x (tonnes)
Porto	110.8	39.1	1.1
Paris-N	769.1	113.0	49.2
Paris-S	13506.2	3956.3	61.2
New York	64458.5	4975.2	1370
Fortaleza	1108.0	55.7	+65.4

Table 13: Reduced fuel, time and pollutant emissions with FRA implemented

As can be obtained from the above table 13, the reductions are very high. This promotes a reduction per year in aircraft emissions, that are released into the atmosphere at high altitudes. At high altitudes the aircraft emissions have greater environmental impact, as it changes directly the amount of accumulated of radiative forcing in the atmosphere and induces cirrus and cloud formation at high altitudes.

5.4. Cost

Costs	in$	in €
	63.15 million	48.64 million

Table 14: Annual costs savings of FRA

	Winter	Summer
Lisbon		
in $	1.40 million	1.75 million
in €	1.07 million	1.35 million
Faro		
in $	0.04 million	0.11 million
in €	0.03 million	0.08 million

Table 15: Annual costs savings of CDO

As can be verified from the above tables 15 and 14, the CDO and the FRA operations represent big economic benefits, which induces directly social benefits.

6. Conclusions

The CDO concept represents an optimized path during descent flight phase. When compared to the conventional descent profile, it is more efficient in terms of safety, as well as it is saving fuel. The aircraft pollutant emissions are truly reduced by the CDO up to 25% and the noise emissions are as well as reduced up to 6 $EPNdB$. In this work the CDO was studied inside an airspace range, between a continuous descent profile with a descent angle of 2° up to 3.3°. The latter is considered the more efficient descent route in terms of the fuel consumption, since stays at higher altitudes throughout a longer time period. Along with these major advantages verified in this work, the flight time and the burned fuel are also reduced, resulting not only in cost and environmental benefits but also in social benefits.

The Free Route Airspace concept is an optimized usage of the airspace at cruise level. This concept allows to reduce the flight time and the burned fuel, thus the pollutant emissions and greenhouse emissions are reduced at high altitudes as well. Along with this, the flight safety is also highly increased, since with this concept the trajectory is not fixed but instead it is very flexible, which allows the aircraft to avoid unfavourable weather conditions. As demonstrated in this work, this kind of operation is more effective for medium and long range missions.

6.1. Outlook and Further investigations

In further investigations the results, regarding the pollutant and noise emissions, obtained here, could be obtained in a more accurate form, by using real data from the performance of the aircraft and from the real weather conditions instead of hipotetical values. In addition to that, the environmental impact and also the cost analysis could be also improved, by using more detailed information on the dispersion of the aircraft emissions in the atmosphere and on the number of movements, respectively.

Progress in the field of Air Traffic Management, flight planning software, as well as navigation systems, will allow full implementation of the two operation concepts presented in this project. In addition to that, they will be an efficient response to the usage of the airspace with the future predicted growth in aviation and at the same time reducing the fuel burn and consequently the emissions produced. Furthermore, investigation on engine and fuel technology, as well as the developments in the renewable energy sector, will be the major contribution in the future, in order to reduce the emissions produced by the aircraft. Certification and regulation of the pollutant species above the LTO cycle, would be also an important tool to limiting the aviation pollutant emissions, as well as noise emissions.

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