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**CONTRIBUCIONES A LA OPTIMIZACIÓN DE ÁREAS DE MANIOBRA TERMINAL GRACIAS A OPERACIONES DE ASCENSO CONTINUO** / *CONTRIBUTIONS TO THE OPTIMIZATION OF TERMINAL MANEUVERING AREAS THROUGH CONTINUOUS CLIMB OPERATIONS*

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# Abstract

The main driver within this dissertation is to gain further insights about the realities of enhancing departure aircraft procedures, based on optimal Continuous Climb Operations (CCOs) within Terminal Maneuvering Areas (TMA). The initial study was applied to a long-range wide-body aircraft. The findings were driven by the advantage offered by the direct analysis of real Flight Data Recorder (FDR) data against the simulated data, obtained through the use of orthogonal polynomials such as Chebyshev polynomials, in partnership with Gauss-type integration rules. Within this work, the calculation of improved trajectories aims at reducing the negative environmental aspects of civil aviation on urbanized areas around airports as well as enhancing the operational cost efficiency. The Multi-Objective trajectory optimization was not only applied to multiple environmental factors such as fuel consumption and noise impacts, but also was constrained by Air Traffic Control (ATC) operational restrictions from a real scenario. The problem, tackled through a multi-objective optimization process based on CCO principles by a Chebyshev-Gauss-Lobatto (CGL) pseudospectral Method, relies on a numerical framework that bears out the benefits in terms of fuel consumption and noise emissions. Therefore, this study promotes the need for investigating, not only the implementation of a CCO generally assumed as an uninterrupted climb departure, but an optimal CCO.

Performing CCO procedures enable the reduction of the environmental footprint and the improvement of the trajectory efficiency when individually operated. However, its operation may affect negatively the overall operational efficiency at TMAs. The estimation of capacity is a matter of paramount importance to all airports planning and analyzing the capacity effects of this particular operational technique on a certain scenario will definitely help on evaluating its potential applicability. As part of this dissertation, departure runway capacity at a particular airport was operationally evaluated when introducing CCOs. The considered trajectories consisted of multi-objective optimized CCOs based on the optimal control theory, using the pseudospectral direct numerical method as a result of the previous studies. These scenarios

allowed addressing of the incremental variations of CCOs versus conventional departures, through fast time simulation, with the objective to assess the effects on the operations.

The International ATM research programs around the world are putting in place significant effort on obtaining innovative solutions for the modernization of ATM. However, these catalogues of ATM solutions are usually focused on individual implementation of them. As a consequence, there are conundrums that remain unresolved from an operational point of view when applying simultaneously more than one of these innovative solutions, at the same scenario. As part of this dissertation, it is envisaged to perform an assessment of the implications when applying two of the most relevant ATM priorities that aims at enhancing the efficiency, predictability, and cost effectiveness of the operations at and in the vicinity of airports. In particular, the considered solutions for this analysis are Airport-Collaborative Decision Making (ACDM) and CCO. The work proposed an optimal control model for minimizing the departure delays of a departure mix of aircraft, considering the performance of optimal CCOs using pseudospectral direct numerical method. Instead of dealing with pure runway sequencing, this work dealt with departure sequencing aspects, tackling the problem with the consideration of conventional flight segments and optimal departure vertical trajectories.

# Resumen

El principal objetivo de esta investigación es obtener una comprensión más detallada de las mejoras que aporta la optimización de los procedimientos de despegue, en base a las características de las Operaciones de Ascenso Continuo (CCO, por sus siglas en inglés) dentro de un Área de Maniobra Terminal (TMA, por sus siglas en inglés). En el trabajo inicial se han realizado estudios de optimización para una aeronave de largo alcance y fuselaje ancho. Los resultados se basan en la ventaja que ofrece el análisis directo de los datos reales de datos de vuelo (FDR, por sus siglas en inglés) en comparación con los datos simulados que se han obtenido mediante el uso de polinomios ortogonales de Chebyshev, junto con las reglas de integración de tipo Gauss. En este trabajo, el cálculo de trayectorias optimizadas tiene el objetivo de reducir los aspectos ambientales negativos de la aviación civil en áreas urbanizadas alrededor de los aeropuertos, así como la mejora de la eficiencia de los costes operativos. La optimización de trayectoria centrada en factores múltiples no solo se aplica a factores ambientales tales como el consumo de combustible y los impactos de ruido, sino que además están limitados por las restricciones operativas del Control de Tránsito Aéreo (ATC, por sus siglas en inglés) para un escenario real. El problema de mejora, que se ha abordado a través de un proceso de optimización de múltiples factores conforme a los principios operacionales de las CCOs mediante un método pseudoespectral de Chebyshev-Gauss-Lobatto (CGL), se basa en métodos numéricos que confirman los beneficios en términos de consumo de combustible y emisiones de ruido. Por lo tanto, este estudio inicial promueve la necesidad de investigar, no solo la implementación de un CCO que es generalmente asumido como una salida de ascenso ininterrumpida, sino un CCO óptimo.

La realización de CCO permite la reducción de la huella ambiental y la mejora de la eficiencia de la trayectoria cuando se opera individualmente. Sin embargo, su operación puede afectar negativamente la eficiencia operativa general en los TMAs. La estimación de la capacidad es de gran importancia para la planificación aeroportuaria y el análisis de los efectos de la capacidad de esta técnica operativa para un determinado escenario ayudará a evaluar su aplicabilidad. Como parte de esta investigación, también se evaluó operativamente la capacidad de la pista

de salida en un aeropuerto en particular cuando se introducen los CCO. Las trayectorias consideradas consistían en CCO óptimos basados en la teoría de control óptima, utilizando el método numérico directo pseudoespectral que se obtienen como parte de los estudios previos. Los escenarios permitieron abordar las variaciones incrementales de los CCO conforme a las salidas convencionales para cada escenario, gracias a simulaciones de tiempo acelerado, con el objetivo de evaluar los efectos en las operaciones.

Los programas internacionales de investigación de ATM en todo el mundo están realizando un esfuerzo significativo para obtener soluciones innovadoras para la modernización de la gestión del tráfico aéreo. Sin embargo, estos catálogos de soluciones ATM se centran generalmente en una implementación individual. Como consecuencia, hay incógnitas que permanecen sin resolver desde un punto de vista operativo cuando se aplican simultáneamente más de una de estas soluciones para un mismo escenario. Como parte de esta investigación, se prevé realizar una evaluación de las implicaciones que se dan al aplicar dos de las prioridades ATM más relevantes que tienen como objetivo mejorar la eficiencia, la previsibilidad y rentabilidad de las operaciones en los alrededores de los aeropuertos. En particular, las soluciones innovadoras consideradas para este análisis son la toma de decisiones colaborativas aeroportuarias (ACDM, por sus siglas en inglés) y las CCO. En el trabajo se propone un modelo de control óptimo para minimizar los retrasos de salida de una combinación de aeronaves de despegue, considerando el rendimiento de los CCO óptimos y utilizando el método numérico directo pseudopectral. En lugar de tratar únicamente con la secuencia en la pista, este trabajo se centra en aspectos de la secuencia de salida, abordando el problema con la consideración de segmentos de vuelo convencionales y trayectorias verticales de despegue óptimas.

# Agradecimientos

Este es un hito muy importante en la carrera de cualquier profesional y tener el honor de escribir estas palabras tienen un gran significado. El esfuerzo y dedicación que esto merece es indescriptible. Las frustraciones de no conseguir los objetivos de las publicaciones suponen un muro que a veces parece infranqueable y solo con el apoyo de los que han sido capaces de confiar en mis posibilidades y habilidades, aún cuando a uno mismo se le hace difícil, se supera.

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# Dedicatoria

**A Alicia, mis padres, hermanos,**

**Javi, Rocío**

**y sobrinos**

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# 1 Introduction

## 1.1 Motivation

Climate Change and Global Warming are two of the most discussed topics in the world at the moment and will be during the coming years. There seems to be enough scientific evidences that manifest the unequivocal changes of the planet as a result of human activity. Unfortunately, our existing level of dependency to the fossil fuels is very high.

Transportation is one of those sectors, which cannot step aside these types of fuels at this point in time. Whilst automotive is achieving significant progresses towards green alternatives, aviation presents significant difficulties that cannot be easily overcome. The encouraging point on aircraft manufacturers comes along with initiatives like Solar Impulse [1]. An airplane of perpetual endurance with the ability to circumnavigate the globe using solar power is simply fantastic. Nevertheless, there is still a long fly before the aviation community will be able to fully embrace “clean” technologies.

## 1.2 Global adherence to ATM environmental efficiency through Air Navigation improvement programmes

Aviation plays a relevant role in the expansion and development of certain areas around the globe, bringing substantial economic and social benefits to a particular region. The continued growth in global air traffic during the last years remains, with substantial expectations of growth in some areas around the World. There are immediate consequences of higher volume of air traffic. These consequences include the negative effects on air quality and the increase of noise levels in the vicinity of airports.

One of the main objectives for any future development is the conservation of the Environment ensuring sustainability of the global climate. International Civil Aviation Organisation (ICAO) establishes in the Global Air Navigation Plan (GANP) “Environmental Protection” as one of the main Strategic Objectives. This strategic objective aims at minimising the adverse environmental effects of civil aviation activities. The ICAO Global Air Navigation Plan (GANP) [2] presents a planning approach based on Aviation System Block Upgrades (ASBUs). At the same time, ICAO Members maintain consistency with ASBU approach through existing global air navigation initiatives as ICAO GANP ASBU Threads and Elements are based on the minimum operational requirements intended to ensure global, regional and national planning improvements according to the prescribed scheduled timeframes.

These global air navigation initiatives for future Air Traffic Management like the Single Sky ATM Research (SESAR) [3] in Europe, The Next Generation Air Transportation System (NextGen) [4] in United States of America and Collaborative Actions for Renovation of Air Traffic Systems (CARATS) [5] in Japan are in progress, aimed at innovative activities for the improvement of the environmental footprint and operational efficiency. In particular, SESAR establishes several Key Objectives that needs to be accomplished by a set of High-Level goals. One of these targets aims at enabling a 10% reduction in the effects flights have on the environment. The enablers that need to be put in place for this target may affect negatively to some other strategic objectives that will lie complex challenges ahead.

### 1.3 Continuous Climb Operation and its relevance to the operational efficiency

What is a Continuous Climb Operation (CCO)? ICAO, within CCO Manual Doc. 9993 [6], defines it as follows; “CCO is an aircraft operating technique enabled by airspace design, procedure design and facilitation by ATC, allowing for the execution of a flight profile optimized to the performance of the aircraft. CCO enables the aircraft to attain initial cruise flight level at optimum air speed and engine thrust settings set throughout the climb, thereby reducing total fuel burn and emissions.”

The importance of this operating technique is such that ASBU methodology establishes a module in Block 0 (B0-CCO) named as “Improved Flexibility and Efficiency in Departure Profiles – Continuous Climb Operations (CCO)”. It is part of the operational concept Full Trajectory-Based Operations and is targeting efficient flight paths (fig.1).

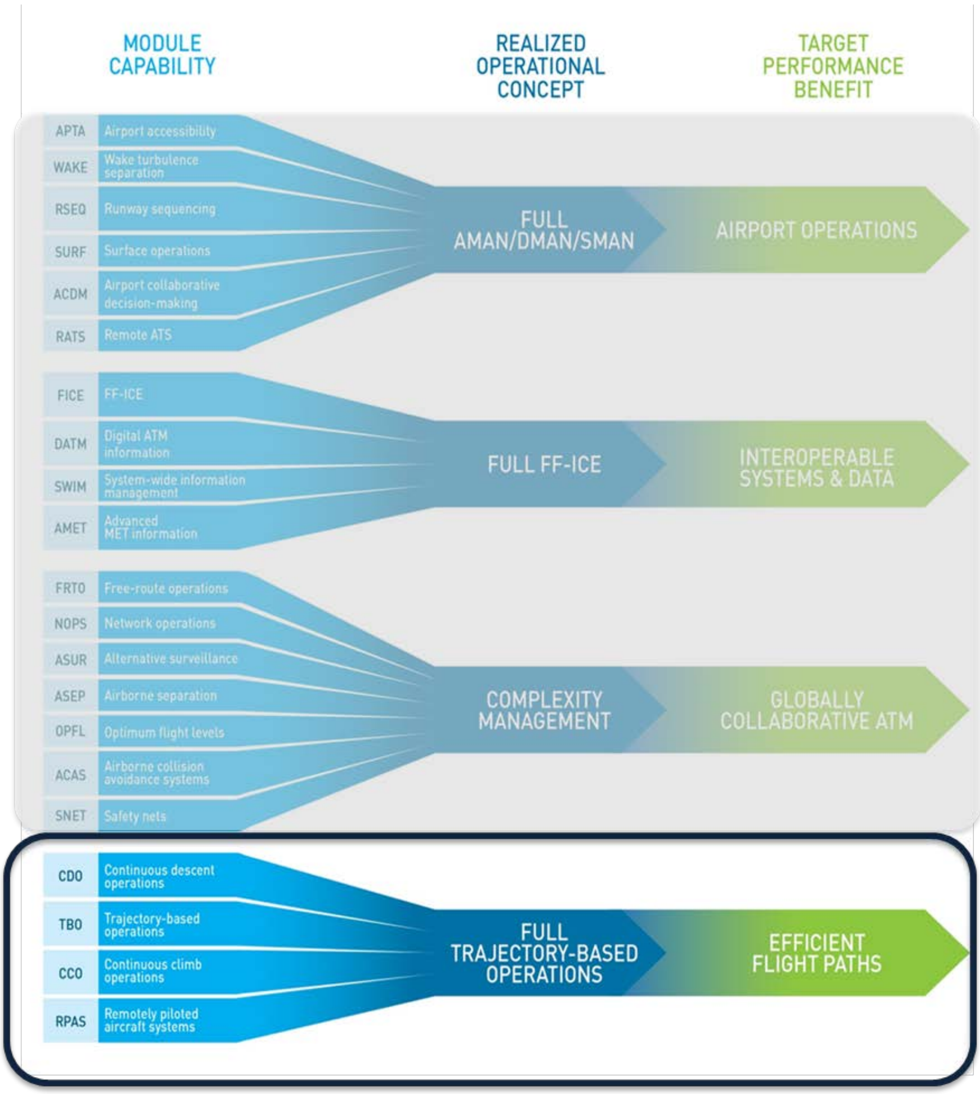


Figure 1: Aviation System Block Upgrades (ASBUs) – Efficient Flight paths

The ICAO's Global Air Navigation Plan 2019-2030 prioritizes environmental gains through PBN terminal procedures as one of the main operational priorities. In line with this priority, ICAO focuses efforts on prioritising CCO that may result in significant reduction in environmental impacts. These environmental benefits for departures are mainly related to fuel savings and reduction of noise impact of noise levels at local communities in the vicinity of airports.

Aerodromes are the defined area on land or water including the associated infrastructure that allows management of arriving and departing traffic. Arrivals and departures are flight operations with high complexity on their execution and control due to the proximity to the airports and their associated operational constraints, which require to be studied with particular dedication. One of the common points to any international ATM initiative is to achieve a more efficient operation without affecting negatively operational safety. The wide variety of airports around the world brings additional difficulties when considering a particular scenario for implementing new operational techniques.

CCO is an operational technique that can provide relevant benefits for departure operations as a large proportion of fuel burns take place during climb departure operations. This provides significant benefits in terms of some of the defined ICAO stakeholder expectations like predictability, environmental efficiency, and cost effectiveness without affecting negatively the safety aspects of the operations. The performance of CCO brings the possibility of noise reduction in the vicinity of airports; in particular it is important for a vertical window between ground and FL100 (10000ft) as well as potential reduction in fuel consumption. The initial climb phase of the flight makes use of a substantial amount of fuel for the entire flight and levelled flight legs, particularly at low altitudes, penalise substantially the overall efficiency of the flight.

Despite the potential reduction of the environmental footprint at local levels, this technique allows airspace users to plan and ideally to fly a trajectory closer to their preferences. This is a significant change thanks to the improvements achieved on technology where the air traffic control is moving towards air traffic management.

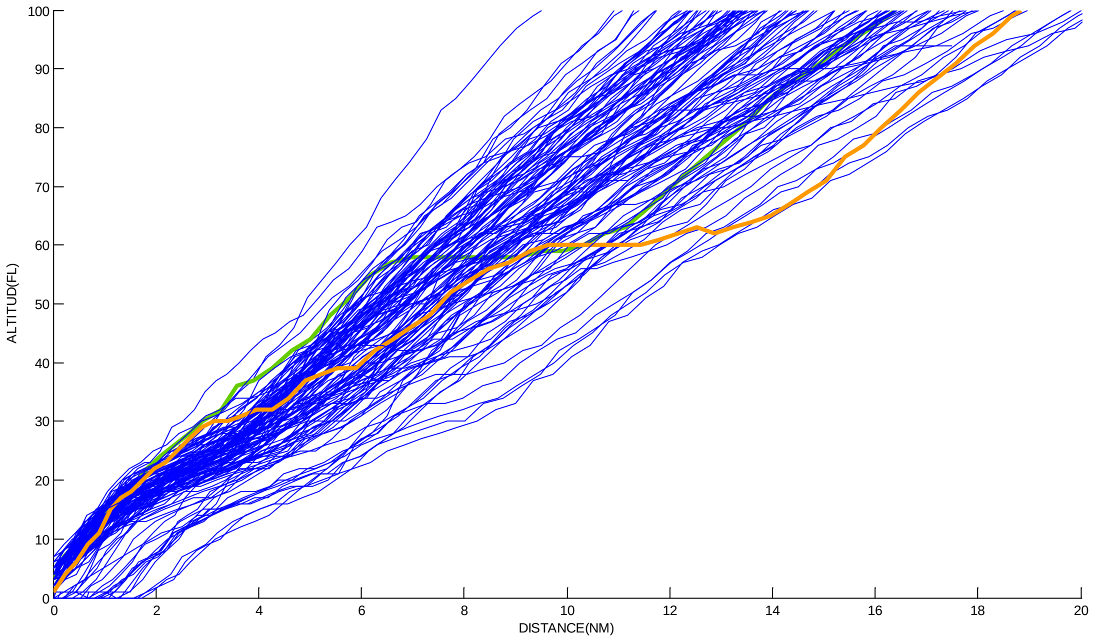


Figure 2: Departure vertical profiles (A320 & B738)

The diagram includes the wide variety of departure vertical profiles when departing from a Spanish airport at sea level for Airbus A320 (A320) and Boeing 737-800 (B738) aircraft. It is possible to distinguish significant dispersion in the swathe of departure profiles, even considering two of the most common aircraft models at many airports around the world. As it is possible to appreciate on the highlighted flights, the aircraft initially climb with aggressive gradient and continue performing leveled-off segments through the departure.

## 1.4 Objectives of this PhD

Numerous studies have been published regarding the environmental and economic optimisation of flight trajectories [7]. In particular, the importance of the Continuous Descent Operations triggered an extensive number of studies, with the objective of reducing fuel consumption and emissions [8], as well as mitigating noise effects [8][9] for arrival traffic.

The departure phase of flight has also been identified as a key area where substantial environmental benefits could be achieved. The overarching objective of this work is to offer the performed investigations about CCOs in order to make aviation more sustainable and efficient.

The main objectives of this dissertation are to:

- Identify the environmental benefits of this tool available to aircraft operators through the multi-objective trajectory optimisation by means of Chebyshev-Gauss-Lobatto (CGL), which therefore allows the analysis of departure profiles along with the quantification of the economic and environmental benefits that CCOs may bring.

However, a new operating technique, which seems to be beneficial when is applied in isolation, may not be quite beneficial in terms of capacity when integrated as part of a complete scenario. This challenge calls for the operational investigation on identifying the capacity effects as a result of integrating optimised CCOs at Terminal Areas. Thus the additional objective is to;

- Evaluate the potential applicability of CCOs to a real scenario, analysing the operational effects they may produce at Terminal Manoeuvring Areas (TMAs), through the estimation of capacity effects when integrating CCOs to a particular scenario.

Furthermore, there exist additional ATM solutions as part of TMA that are promoted by international ATM programs like Airport-Collaborative Decision Making (ACDM) [10], which are essentially focused at enhancing the overall efficiency of airport operations,

- Assess the effects that CCOs may present within a consolidated world class solution like A-CDM through an advanced departure management model that cover this efficient type of operations.

Figure 3: Image representing a departure aircraft at earlier stages of its climb procedure. *Alisdair Miller Photography*

## 1.5 Scope and limitations

The initial phase of this research was focused on individual trajectory optimization problem, i.e. the effects on fuel consumption and noise for multiple operations have not been directly tackled in this first phase of the studies. The main objective of the initial works aimed at providing more convincing evidences about enhancing departure operational procedures based on CCOs. The multi-objective trajectory optimisations were not only applied to multiple environmental factors, in particular fuel consumption and noise impacts, but also were constrained by real operational restrictions from real scenarios. This optimisation problem was tackled through multi-objective optimisation process based on CCO principles by Chebyshev-

Gauss-Lobatto (CGL) Pseudospectral Method, which establishes the numerical framework for the simulations.

Considering the importance that the "data" is gaining nowadays, data analytics seem to be one of the most relevant and influential topics around the world. World ATM Congress, which is the world's largest international air traffic management exhibition and conference, has covered in 2018 edition workshops about the use of Big Data techniques in ATM. In case of this dissertation, data analytics has provided relevant contributions at several stages.

The findings from the initial phase, referred in the paragraph above, were obtained thanks to the analysis of Flight Data Recoded (FDR) against simulated data. This bears out the importance of the data in this type of investigations. The data does not only bring the benefits of performing like-for-like parameter comparisons, but also allow characterisation of trajectories and parameterisation of scenarios. Two main types of data have been utilised throughout the progress of these investigations, these are simulated and real data. The latter could be obtained from different sources. The characteristics of real data depend on the type of sources and are reflected on their frequency, accuracy, quality and availability amongst others.

Unfortunately the access to real data is very limited and may require confidentiality agreements or memorandum of understandings in order to allow for its use. The author had the opportunity to learn from relevant experts in this field that allowed him to enhance his data management and analysis skills according to the characteristics that present each different data source.

The main second stage of this work was focused on analysing the effects of this operational technique as part of a wider scenario. The performance of optimal CCO trajectories enables the reduction of the environmental footprint when operated in isolation, but may affect negatively to the overall operational efficiency at Terminal Manoeuvring Areas (TMAs). Considering that capacity is a matter of paramount importance to the ATM Community, the analysis of capacity effects of this particular flight technique on an scenario will definitely bring clarity on its potential applicability.

Last but not least and in view of the obtained results, it was decided to evaluate CCO implementation along with Airport-Collaborative Decision Making (ACDM) that is one of the most relevant ATM solution currently implemented in some of the main airports around the world.

## 1.6 Outline of the dissertation.

This structure of this dissertation is as follows;

Chapter 2 describes the state of the art for Continuous Climb Operations (CCOs).

Chapter 3 presents the mathematical framework.

Chapter 4 includes the fundamentals for the multi-facto optimization.

Chapter 5 gathers the insights about the environmental realities of enhancing departure aircraft procedures, based on optimal CCOs.

Chapter 6 captures the analysis regarding the departure runway capacity effects of integrating optimized CCOs.

Chapter 7 covers an assessment of the implications when applying Airport-Collaborative Decision Making (ACDM) and CCOs.

# 2 Continuous Climb Operations (CCOs)

## 2.1 Continuous Climb Operations Procedures

Global air navigation initiatives for future Air Traffic Management (ATM) like the Single Sky ATM Research (SESAR) [3] in Europe, The Next Generation Air Transportation System (NextGen) [4] in United States of America and Collaborative Actions for Renovation of Air Traffic Systems (CARATS) [5] in Japan are in progress, aimed at innovative activities for the improvement of the environmental footprint and operational efficiency. The optimization of vertical profiles is one of the main drivers on these global initiatives. Among them, techniques like Continuous Descent Operations (CDOs) and Continuous Climb Operations (CCOs) aim at improving aircraft's fuel efficiency.

Moreover, the International Civil Aviation Organization (ICAO) has prioritized within the Global Air Navigation Plan [2], the usage of continuous operations among other ATM initiatives. Operating techniques, such as continuous climb operations (CCOs) [6] can significantly reduce the environmental footprint in living areas around the airports. Moreover, this technique may affect positively to Efficiency, Environment and Safety Key Performance Areas as per Doc. 9883 [11].

A CCO is generally defined as an uninterrupted climb flight operation allowing the aircraft to attain initial cruise flight level at optimum air speed with optimal thrust settings [6]. This technique potentially allows the airspace user to operate its departure according to its own vertical profile preferences, whilst avoiding unnecessary thrust variations. From an operating cost perspective, this provides the airline with an additional tool for improving the overall cost efficiency.

An optimum vertical flight path for arrival or departure takes the form of a continuous profile. However, the calculation of the optimal path according to specific factors may not be sufficient for the implementation of them at a particular scenario. ATC must provide safe and expeditious Air Traffic Services and the characteristics of these procedures may impact negatively in the overall Efficiency of the operation. Therefore, as highlighted within [6], it is necessary to combine the expertise from ATC, airspace designers and airlines for the operational implementation.

Figure 4: Image representing different departure aircraft at earlier stages of their climb procedures. *Alisdair Miller Photography*

The optimization of flight trajectories for terminal operating procedures has been a problem extensively tackled during years, particularly focused on arrival procedures [8], [9]. Limited research has been conducted in terms of 'pure' CCOs, as the benefits did not seem to be noteworthy. However, considering during climb phase engines usually run close to full throttle, there exist potential for reducing the environmental footprint in living areas around the airports. In this regard, McConnachie et al. [12] presented the evidences for environmental performance change in case CCOs are applied at certain airports. Nevertheless, it was plausibly assumed that a CCO is just an uninterrupted climb.

The potential integration of CCOs along with PBN, Continuous Descent Operations (CDO) [13] and the management of airspace may produce remarkable effects on efficiency, predictability, safety and environment (through minimization of fuel use, emissions and noise).

The inefficiency of flight operations triggers delays in many Terminal Maneuvering Areas, which may affect other airspaces around the world (knock-on effect). Any opportunity for increasing capacity, enabling fuel efficiency for the climb/descent profile as well as improving overall efficiency should be considered as a priority.

## 2.2 Operational aspects of CCOs

A significant proportion of fuel burn takes place during the climb phase and operating at optimum flight level allows the improvement of flight fuel efficiency and the minimization of atmospheric emissions. CCO benefits are directly related to noise reduction, fuel burn and hence emissions but also increase flight path predictability. Regarding the latter, Air traffic controllers and pilots will definitely appreciate this operational benefit.

The optimization of CCO will vary depending on the aircraft type, mass, performance and environmental condition but also will depend on the operational constraints. In this regard, speed constraints in combination with level segments represent a severe constraint that affects the operation.

The ICAO CCO Manual [6] states that ideally, in order to maximize the benefit of a CCO, it should start at take-off, encompassing the Departure Noise Abatement Procedures and Noise Preferred Route requirement immediately following take off and continue through to the initial cruise climb. The approach followed within this dissertation for the optimization of the CCO is tackled through a multi-objective optimization process based on CCO principles by a Chebyshev-Gauss-Lobatto Pseudospectral Method. Relevant remarks are shown later in this document regarding the outlines from CCO Manual and the conclusions achieved through the proposed methodology.

The balance between promoting CDOs and CCOs at Terminal Airspaces requires the particular assessment and operational decisions based on the local priorities. However, yet the CDOs and CCOs have different fundamental differences, the operational analysis of arrival and departure flows will be of paramount importance to define the most convenient at each time of the day considering the modes of operation.

From an operational point of view, the operational manual at some Area Control Centers (ACC) may be impacted by the introduction of a new Airspace procedure. There exist situations where ATC may not be willing to avoid leveled traffic, for example when transferring traffic between adjacent controllers. In other words, if a departing aircraft requires to be transferred from ATC Tower jurisdiction to an ATC Approach jurisdiction, it will be mostly required to establish it at a specific flight level so the level of uncertainty will not increase.

Despite the initial modules of this dissertation are mainly focused on individual aircraft CCO-based departure optimization, the followings are mainly focused on determining the operational effects that these type of operation may bring. In particular, the overall effects of an optimal CCO on runway capacity have been tackled.

### 2.3 Vertical Flight Path

Acting on the vertical flight profile is an efficient method to mitigate aircraft noise footprint on departures. Whether lateral adjustments are not possible or the trajectory is constrained by overflying certain points, the vertical flight path has potential to improve aircraft noise and fuel consumption. Moreover, additional restrictions like the need to enforce a particular ATM or safety constraint may limit the aircraft from flying its optimal trajectory. The main factors encompassing the performance of a departure operation are the tactical constraints.

In terms of noise reduction departures, the most extended and widely used procedures for noise mitigation are the so-called ICAO Noise Abatement Departure Procedures (NADP) [14]. There exist two published procedures for this purpose; one of them mainly focused on protecting areas located in the vicinity of the airports while the other one is focused on protecting distant areas from the airports. However, the main limitation of these procedures is the genericness and as a consequence, there seems to be difficult that they may address the specific environmental constraints of certain scenarios. Some authors, like [15] have worked extensively on the optimization of NADPs.

### 2.4 Conventional departures versus Optimized CCOs

Traditionally, tactical controllers manage aircraft within their airspace domain and provide clearances to specific altitudes based on the characteristics of the traffic in terms of complexity and airspace layout. A conventional departure trajectory, which has been vertically limited, presents several level-offs before reaching the cruise level.

There is a limit to the number of aircraft that controllers can keep track of at one time within their area of responsibility or jurisdiction. Hence, airspace has to be subdivided in airspace sectors. One of the consequences is that flights evolving through controlled sectors require leveled segments as a result of operational needs. However, there may be other reasons why the leveled segments are required, like performance limitations of aircraft. These leveled segments on the vertical profile penalize the aircraft efficiency and prevent the aircraft from flying its ideal trajectory. Conversely, the performance of an optimized CCO that allows the aircraft to attain initial cruise flight level at optimum air speed with optimal thrust settings brings noteworthy benefits to the flight efficiency. The diagram below illustrates the standard departure and an optimized CCO where can be appreciated the differences between their departure flight paths.

The successful application of a CCO should not be simplistically reduced to the operation of an uninterrupted climb procedure, which implies inexistent level-off segments. There exists a variety of optimal departure procedures depending on different factors like; aircraft, airport, runway, Standard Instrument Departure (SID) and so on.

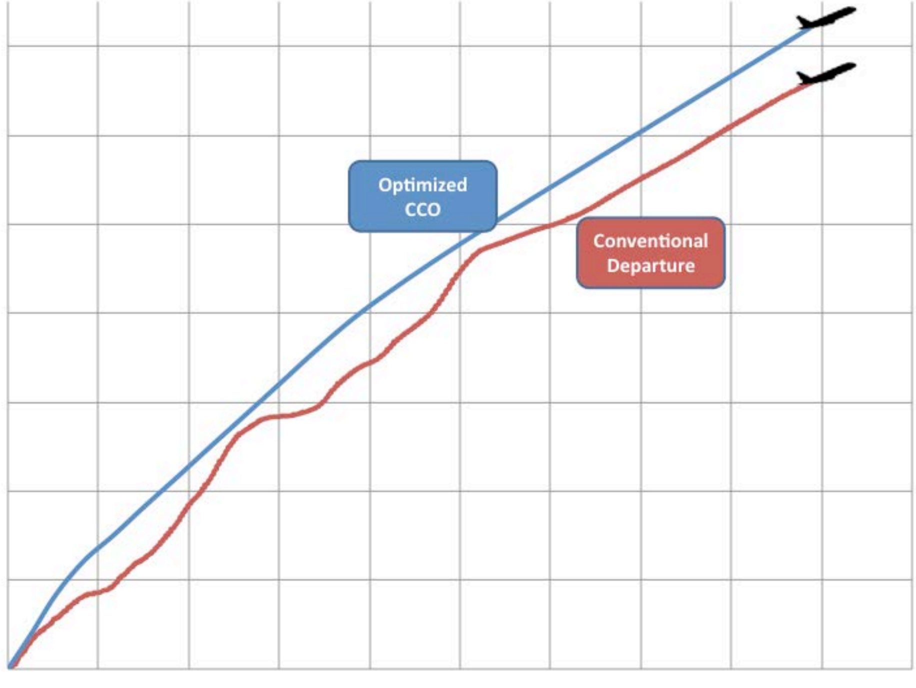


Figure 5: Departure flight paths: Optimized CCO versus standard departure

Ideally, CCO should allow aircraft to follow a flexible, optimum flight path that delivers major environmental and economic benefits (reduced fuel burn, gaseous emissions, noise and fuel costs) without any adverse effect on safety [6]. Herein, CCO operations would bring departing aircraft the capability to climb continuously, to the greatest extend possible. Deployment of optimized CCO throughout Europe has been identified as very beneficial to all European ATM system stakeholders and also may help on addressing the environmental challenges it faces. Eurocontrol has published that on average; the benefit of optimizing CCO/CDO would result in fuel savings of up to 350,000 tones of fuel (1m tones+ $CO_2$) or 150+ million Euro.

In Europe, the implementation of CCO and CDO operations was encouraged based on "as-much-as-you-can-basis' and also the harmonization in terms of what actually constitutes a CCO.

In terms of CDO, the efforts have been significantly higher than CCO. Numerous Initiatives have been nationally and internationally applied in order to determinate the potential benefits of optimizing the CDO in terms of fuel savings, emissions reduction and fuel cost.

In this regard, it is worth mentioning the Spanish initiative for enabling the operation of a semi best Continuous Descent Operations, based on Optimized Profile Descent (OPD) concept. OPD is an operational method promoted by Federal Aviation Administration (FAA) [13] for going around the CDO problem by ensuring an optimal balance between aircraft performance, delivery of environmental benefits and air traffic control requirements.

### 2.4.1 Phase 1: Optimized Profile Descent Approaches (OPTA) project

The initial phase was Optimized Profile Descent Approaches (OPTA) project [1] [2] that was promoted by ENAIRE–Spanish ANSP and the former Aena. During this phase, the objective was to provide a control technique and a procedure design with which it enabled air traffic controllers to support the reduction of emissions and the optimization of fuel consumption in the TMA through the use of Optimal Descent Approaches from Top of Descent.

During the development of the project the OPD concept was applied and tailored into the Palma TMA environment and specifically to the western STARs to PMI. The project included various assessments (Business, Human Performance, Safety and Environmental) and was validated by tools such as FTS (Fast Time Simulation) and RTS (Real Time Simulation), coupled with commercial flights provided by AirEuropa through its 738 fleet of aircraft.

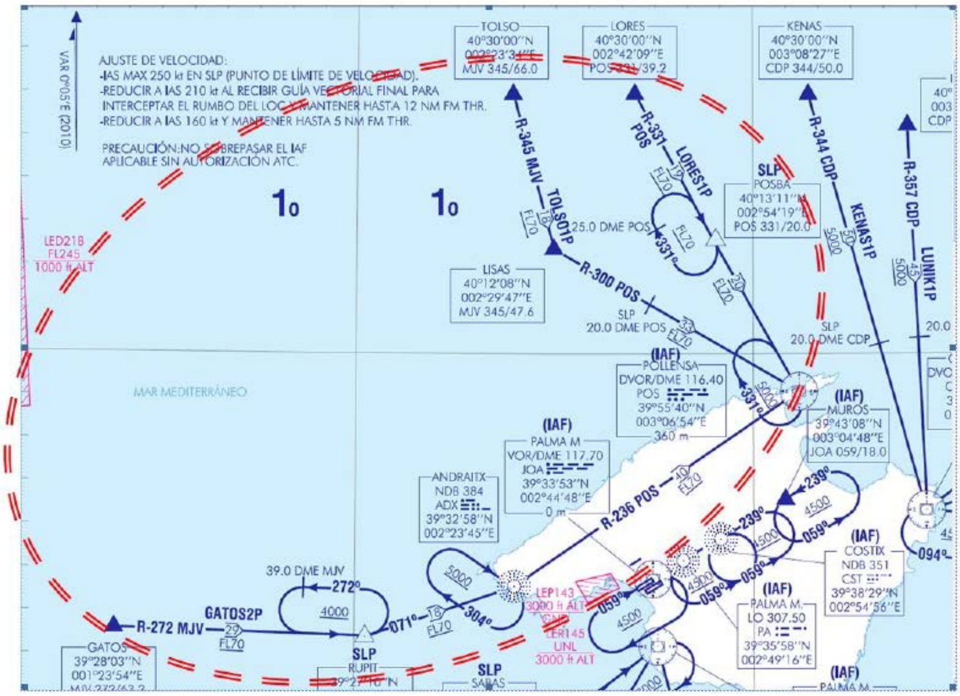


Figure 6: OPTA study area and STARs

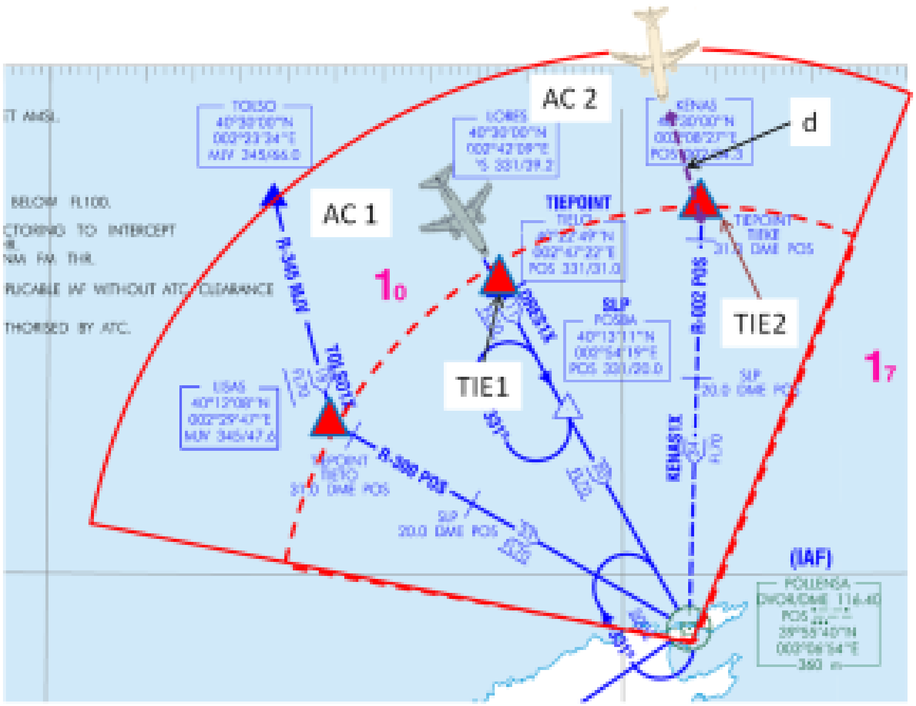


Figure 7: OPTA-IN study area and STARs

This is based on the OPTA concept which, differs from the current procedures mainly on the descent profile that resembles the best performance of an aircraft in descent phase. From the air traffic controller point of view, it requires the use of speed adjustments, enabling the aircraft to fly its preferred continuous path through pre-defined speed-altitude windows keeping its predictability.

### 2.4.2 Phase 2: Optimized Profile Descent Approaches –Implementing Windows (OPTA-IN) project

The second phase, Optimized Profile Descent Approaches–Implementing Windows (OPTA-IN) [16] [17], sponsored by the SJU inside the Integrated Flight Trials and demonstration activities framework (AIRE III) was developed with the aim to be the demonstration platform and therefore the subsequent validation step for the implementation of the OPTA concept as a short-term solution.

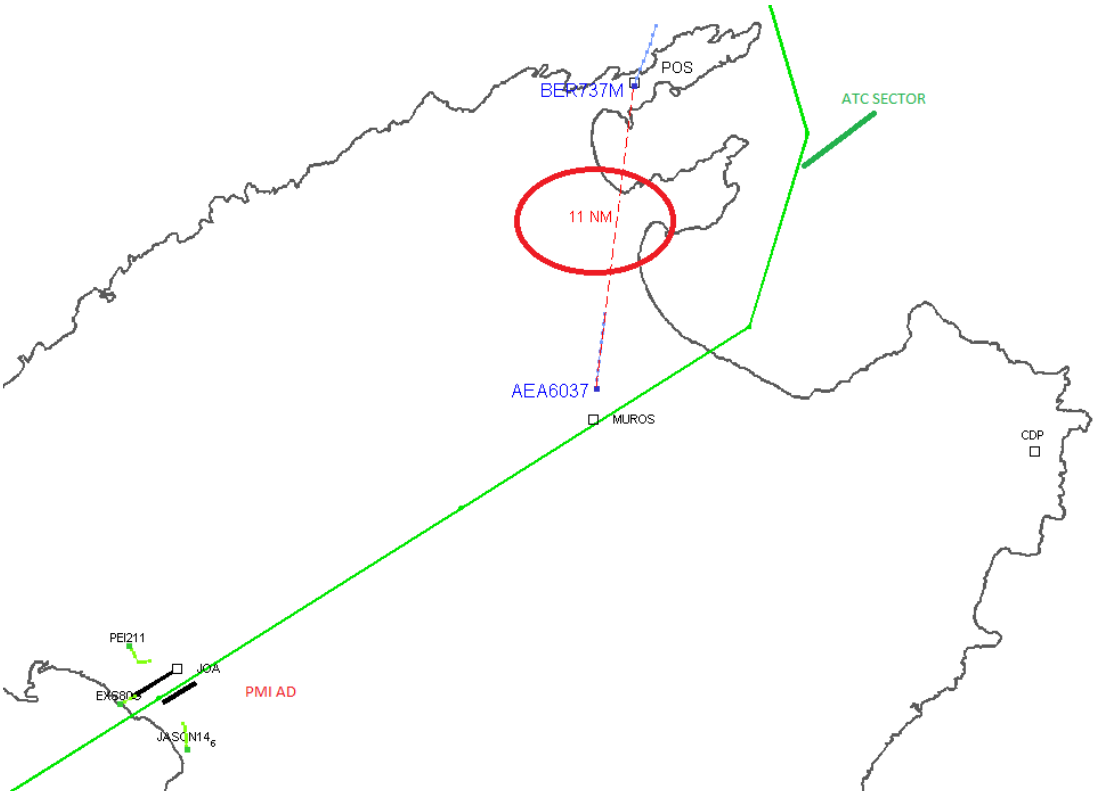


Figure 8: OPTAIN Technique not affecting normal operation

In summary, the core of the project was to demonstrate by means of real live traffic: the OPTA concept; the ATC-control techniques together with assurance and verification of the procedure; the operational requirements from [18] and Acceptance/testing of the support tool which would aid the air traffic controllers.

The designated airspace was the Palma TMA (ENAIRE) situated in FIR Barcelona (SPAIN), where the OPTA concept was simulated in OPTA project and the traffic density conditions allowed for the OPTA-IN project to be adequately demonstrated thanks to the seasonality of the traffic.

Last but not least, the author has been a co-author of the work presented during the eight edition of International Conference for Research in Air Transportation (ICRAT) 2018 regarding the Operational validation of the OPTAIN-SA tool [19].

# 3 Mathematical Framework

## 3.1 Optimal Control

Control theory aims at studying the behavior of dynamical systems based on control inputs. Tracking control and terminal control are two categories to classify the control systems; where the former aims at maintaining the state of the system in the vicinity of a nominal path and the latter aims at guiding a system from an initial state to a final state in a given time. The control inputs could be open-loop and closed-loop, depending on the knowledge of the actual state of the system. The optimization of flight trajectories has been a problem extensively tackled during years. An early and one of the most relevant studies that applied optimal control theory was [20].

The mathematical method used for the optimization of the CCO is based on optimal control theory, which aims at determining the control input that will cause a system to achieve the control objectives, whilst satisfying the constraints and also optimizing some performance criterion. The trajectory optimization problem was solved following an open loop terminal control problem that allows the constraints acting on the dynamical system to be considered in a way that the obtained trajectory will be admissible.

Commercial aircraft trajectory problems have been tackled through open loop optimal control techniques [21][22][23][24][25]. However, optimal control problems are characterized for being highly nonlinear and thus, it becomes certainly difficult to find analytical solutions. Numerical methods are typically used for this purpose and direct methods fit the approach for the trajectory optimization problem. A simplistic description of direct methods could be presented as discretizing the optimal control problem at the nodes of discretization that results in a NLP ready to be solved.

## 3.2 Optimal Control Problem

With the aim of facilitating the discussion, consider the following optimal control problem (OCP):

$$\min\ J(t, x(t), u(t), l) = E\left(t^F, x(t^F)\right) + \int_{t^I}^{t^F} L(x(t), u(t), l)dt\ ; \qquad (1)$$

subject to:

$\dot{x}(t) = f(x(t), u(t), l)$ , dynamic equations;

$0 = g(x(t), u(t), l)$, algebraic equations;

$x(t^I) = x^I$, initial boundary conditions;

$\psi(x(t^F)) = 0$, terminal boundary conditions;

$\phi_l \leq \phi[x(t), u(t), p] \leq \phi_u$, path constraints.

Variable $t \in [t^I, t^F] \subset \mathbb{R}$ represents time and $l \in \mathbb{R}^{n_l}$ is a vector of parameters. Notice that the initial time $t^I$ is fixed and the final time $t^F$ might be fixed or left undetermined. $x(t): [t^I, t^F] \rightarrow \mathbb{R}^{n_x}$ represents the state variables. $u(t): [t^I, t^F] \rightarrow \mathbb{R}^{n_u}$ represents the control functions, also referred to as control inputs, assumed to be measurable. The objective function $J: [t^I, t^F] \times \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_l} \rightarrow \mathbb{R}$ is given in Bolza form. It is expressed as the sum of the Mayer term $E(t^F, x(t^F))$ and the Lagrange term $\int_{t^I}^{t^F} L(x(t), u(t), l)dt$.

Functions $E: [t^I, t^F] \times \mathbb{R}^{n_x} \rightarrow \mathbb{R}$ and $L: \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_l} \rightarrow \mathbb{R}$ are assume to be twice differentiable. The system is a DAE system in which the right hand side function of the differential equations $f: \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_l} \rightarrow \mathbb{R}^{n_x}$ is assumed to be piecewise Lipschitz continuous, and the derivative of the algebraic right hand side function $g: \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_l} \rightarrow \mathbb{R}^{n_z}$ with respect to $z$ is assumed to be regular. $x^I \in \mathbb{R}^{n_x}$ represents the vector of initial conditions given at the initial time $t^I$ and the function $\psi: \mathbb{R}^{n_x} \rightarrow \mathbb{R}^{n_q}$ provides the terminal conditions at the final time and it is assumed to be twice differentiable. The system must satisfy algebraic path constraints given by the function $\phi: \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_l} \rightarrow \mathbb{R}^{n_\phi}$ with lower bound $\phi_l \in \mathbb{R}^{n_\phi}$ and upper bound $\phi_u \in \mathbb{R}^{n_\phi}$. Function $\phi$ is assumed to be twice differentiable.

## 3.3 Numerical Methods

Optimal Control problem has the characteristic of being highly nonlinear and thus, it is very difficult to find the analytical solution. Therefore, the most common practice is to make us of numerical methods. In this regard, there exist three main approaches to numerically solve continuous time optimal control problems such as OCP:

**Dynamic Programming methods**: These methods are based on a transformation of a complex problem into a sequence of simpler problems called stages, where this sub-problem is linked together by a recurrence relation. It was introduced by Bellman [26] and the optimality criterion is based on Hamilton-Jacobi-Bellman partial differential Equation.

**Direct methods:** These methods translate the infinite dimensional problem into a problem with a finite dimensional parameterization, allowing thus to solve the finite dimensional problem through optimization. The approach could be defined, as “first discretize and then optimize” strategy and they do not make use of the first-order necessary conditions of the continuous problem. A common strategy followed is to translate the original problem into a NLP problem that is consequently solved through mathematical programming techniques [27][28].

**Indirect methods:** The optimal control problem is turned into a two-point boundary values-problem that maintains the same mathematical information as the initial problem and requires its discretization by some numerical technique for being solved. The main feature of indirect method is the fact that relies on Pontragin’s Maximum Principle [29]. The approach could be defined as “first optimize and then discretize” strategy.

## 3.4 Direct collocation methods

Direct collocation method discretizes the trajectory optimization problem, usually by converting the original trajectory optimization problem into a nonlinear program. These methods allow the discretization of a continuous trajectory optimization problem by approximating all of the continuous functions in the problem as polynomial segments. Polynomial are used because the can be represented by a finite set of coefficients and also because the low complexity on computing integrals and derivatives of polynomials. Therein, a suitable interpolating function would be such that it goes through the state values and maintains the derivatives at the nodes, spanning an interval of time.

The interpolating function requires to be evaluated at the collocation nodes, which are the nodes between points. At each of these points, a constraint equating the interpolating function derivative to the state derivative function needs introduced to ensure that the equations of motion are approximately satisfied across the entire interval of time.

One of the most relevant families of collocation methods is the pseudospectral, where state and control equations are parameterized through global polynomials (Legendre and Chebyshev) and the differential algebraic equations are evaluated at the nodes or the collocation points derived from a Gaussian quadrature [30]. In case of the Legendre pseudospectral methods, the quadrature nodes require to be computed numerically as zeros of the Lagrange polynomials. On the other side, in the case of the Chebyschev pseudospectral methods the quadrature nodes come from explicit formulas. These methods can be further classified attending at the class of collocation points, typically Gauss, Gauss-Radau or Gauss-Lobatto collocation points [31].

## 3.5 Chebyshev Pseudospectral Method

The Chebyshev Pseudospectral Method, which has demonstrated advantage over indirect methods, is widely used in engineering applications, especially on trajectory optimization problems [32]. This spectral method utilizes orthogonal polynomials instead of piecewise continuous polynomials when approximating state and control variables.

F. Fahroo & I. M. presented at [33] the demonstration of the fact that Chebyshev-Gauss-Lobatto (CGL) method yields more accurate results than those obtained from the traditional collocation method. Recently, in [34], an intensive analysis on different direct collocation methods to solve a classical problem on ATM was presented. Once again, pseudospectral collocation method has proven better results on accuracy and computational time but uncertainties in vertical trajectories during climb/descent.

These polynomials are typically defined over the interval $[-1, 1]$, which are the eigenfunctions of a Sturm-Luiouville problem. Thus, it is required to reformulate the Optimal Control Problem (OCP) using the following mapping function

$$t = \frac{t^f + t^0}{2} + \frac{t^f - t^0}{2}\,\tau \tag{2}$$

Regards to that form, the OCP could be rewritten considering; The initial time is $\tau = -1$ and the final time is $\tau = 1$, the dynamic equations in this problem are $\dot{x}(\tau) = \frac{t^f - t^0}{2} f(x(\tau), u(\tau), p)$ ,the path constraint is $\phi[x(\tau), u(\tau), p] \leq 0$ and the algebraic equations is $g(x(\tau), u(\tau), p) = 0$ . It is necessary to approximate each of the state variables as:

$$x(\tau) = \sum_{k=0}^{N} \frac{W(\tau)}{W(\tau_k)} x_k \phi_k(\tau) \tag{3}$$

where the index $k$ denotes the node for the global Lagrange interpolating polynomial of $N$ order, W is a positive weight function, $x_k$ denotes the state value for node k and $\phi_k(\tau)$ denotes the general expression for a Lagrange interpolation polynomial of $N$degrees which satisfies $\phi_k(\tau_I) = 0$ and $\phi_k(\tau_I) = 1$ where $i \neq k$, i.e.

$$\phi_k(\tau) = \prod_{i=0\ i\neq k}^{N} \frac{\tau - \tau_i}{\tau_k - \tau_i} \tag{4}$$

It must be noticed that $i$ is another index which denotes the node for the global Lagrange interpolating polynomial of order $N$. It is important to highlight that collocation points in Pseudospectral Methods depend on the approximating polynomial and in this case, as a Chebyshev method, the collocation points have an explicit formula. The polynomials for this case; $T_k(\tau), k = 0, 1, \ldots, N$ are the eigenfunction of the singular Sturn-Liouville problem:

$$\left(\sqrt{1-\tau^2}\, T_k'(\tau)\right)' + \frac{k^2}{\sqrt{1-\tau^2}} T_k(\tau) = 0 \tag{5}$$

The solution to this problem satisfies the following relation:

$T_k = \cos(k\theta), \theta = \arccos(\tau)$

If the trigonometric relation; $\cos(k+1)\theta + \cos(k-1)\theta = 2\cos(\theta)\cos(k\theta)$ is applied, the solution to the problem results in the following recursive relation:

$$T_{k+1}(\tau) = 2\tau T_k(\tau) - T_{k-1}(\tau) \tag{6}$$

where $T_0 = 1$ and $T_1 = \tau$ . Chebyshev Pseudospectral Methods utilize three different types of collocation points among those in the family of the Chebyshev- Gauss points, but the one, which has been used to solve this problem in this dissertation, is the Chebyshev-Gauss-Lobatto (CGL). This method for collocating points includes both boundaries $\tau = -1$ and $\tau = 1$ as collocation points.

$$T_k(\tau) = \cos\left(\frac{\pi k}{N}\right), k = 0, \ldots N \tag{7}$$

### 3.5.1 Application to differential equations

The advantage offered by the use of orthogonal polynomials such as Chebyshev polynomials is the close relationship to Gauss-type integration rules. These methods offer accuracy and rapidity when performing trajectory optimization as Fahroo and Ross, [33], concluded on their research.

Time derivative of the state vector, $\dot{x}^N(\tau)$, is expressed in terms of the approximate state vector $x^N(\tau)$ at the collocation by the use of a differentiation matrix with the aim of transforming the OCP into a NLP. Therefore, it is possible to express the derivative $\dot{x}^N(\tau)$ in terms of $x^N(\tau)$ at the collocation points by the following equation:

$$\dot{x}(\tau_j) = \dot{x}(t_j)\frac{dt}{d\tau} \approx \sum_{k=0}^{N} x_k \dot{\phi}_k(\tau_j) = \sum_{k=0}^{N} D_{jk} x_j \tag{8}$$

The Lagrange interpolation polynomial of order N is given by

$$\phi_k(\tau(t)) = \frac{(-1)^{k+1}}{N^2 c_k} \frac{(1-\tau^2)\dot{T}_N(\tau)}{\tau - \tau_k} \tag{9}$$

Where,

$$c_k = \begin{cases} 2, & k = 0, N \\ 1, & k = 1, \dots N-1 \end{cases} \tag{10}$$

and the first derivative matrix yields:

$$D_{jk} = \begin{cases} \dfrac{c_j}{c_k}\dfrac{(-1)^{j+k}}{\tau_j - \tau_k}, & j \neq k, \\ -\dfrac{\tau_k}{2(1-{\tau_k}^2)}, & 1 \leq j = k \leq N-1, \\ \dfrac{2N^2+1}{6}, & j = k = 0, \\ -\dfrac{2N^2+1}{6}, & j = k = N. \end{cases} \tag{11}$$

Since the problem has been formulated over the time interval $[1, -1]$, and the CGL points lie in the interval $[-1, 1]$, it is necessary to perform a symmetric transformation.

In this investigation, the operational flight paths were obtained through multi-objective optimization process based on CCO principles by a CGL pseudospectral method. The calculations were executed through a hand-tailored software tool implemented on AMPL modeling language [35] for Airbus A319 and A330 aircraft, using IPOPT as NLP solver. The latest Base of Aircraft Data (BADA 4.1 [36]) supported AMPL self-implemented optimization model. AMPL is an algebraic modeling system for mathematical programming of large-scale optimization problems. For sake of clarity, solver is defined as the number-crunching algorithm that computes optimal solutions. The calculated optimal trajectories were stored in a database for further processing.

## 3.6 Aircraft Performance

This section aims at providing the aircraft dynamics equations considered for this dissertation. In order to do so, the following sections summarize the steps for obtaining a set of differential equations that conforms the equations of motion of an aircraft.

The translational equations (force, $f = m.a$) and rotational equations (moment, $M = I.\alpha$) are the so called six-degree of freedom (6 DOF) equations of motions. In terms of trajectory analysis, the translational equations are uncoupled from rotational equations by assuming that the airplane rotational rates are negligible and control surface deflections do not affect the forces. The main purpose will be the determination the three-degree of freedom (3 DOF) equations of motion for flight in a vertical plane over a flat earth.

### 3.6.1 General Assumptions

For the study of aircraft trajectory, is necessary to assume the forces act at the center of gravity of the aircraft, considered as a variable-mass model with 3 DOF. For deriving the equations of motion for the non-steady flight in a vertical plane over a flat earth, the following physical model needs to be assumed:

1. The aircraft is modeled as a variable-mass point;
2. The aircraft is a conventional jet airplane with fixed engines and a right-left plane of symmetry;
3. The forces (thrust, aerodynamics and weight) act at the center of gravity of the aircraft and the thrust and the aerodynamic forces lie in the plane of symmetry;
4. Flat earth model that means the acceleration of gravity is constant and perpendicular to the surface of the earth. The earth model is flat, non-rotating and an approximate inertial referenced frame;
5. The atmosphere is at rest relative to earth and the atmospheric properties are functions of altitude.

### 3.6.2 Coordinate systems and axes.

With the aim of obtaining the equations of motion, the vector equations are considered in their matrix form. In order to do so, the projection of vectors in a coordinate reference system is necessary. For each coordinate system that moves with the aircraft, the x and z axes are in the plane of symmetry of the aircraft and the y axis is such that the system is right handed.

The following are the coordinate systems and axes considered for obtaining the equations of motion:

**Earth-Centered Inertial (ECI) reference system** $\mathrm{I}\ (\mathrm{O}, \mathrm{x_I}, \mathrm{y_I}, \mathrm{z_I})$: The xy plane coincides with the Earth's equatorial plane.

- Origin: $O$ – Earth center;
- $x_I$ axis - Permanently fixed in a direction relative to the celestial sphere (does not rotate like earth does);
- $y_I$ axis - completes the right handed system;
- $z_I$ axis - Lies at a 90 degrees angle to the equatorial plane and extends through the North pole.

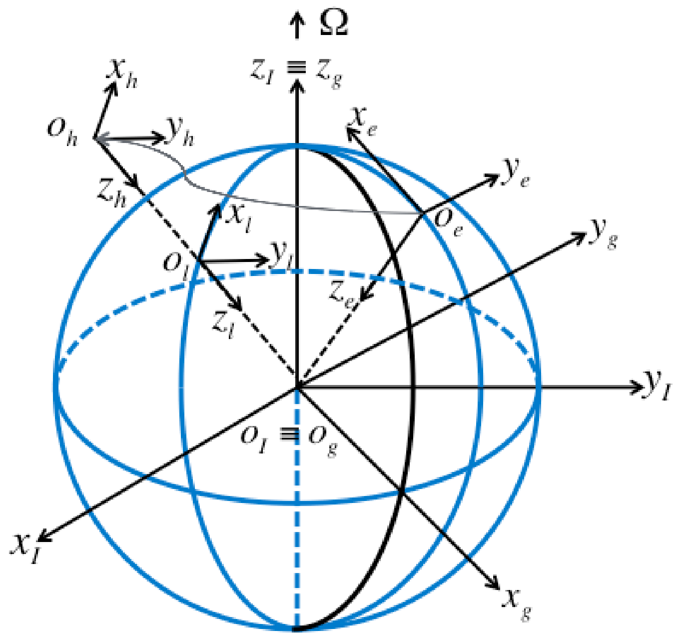


Figure 9: Reference axes systems

**Earth ground (Topocentric) axes system** $\mathbf{E}\ (\mathbf{O}, \mathbf{x_e}, \mathbf{y_e}, \mathbf{z_e})$**:** the ground axes system is fixed to the surface of the earth at mean sea level, where xz is the vertical plane and xy is the horizontal plane.

- Origin $\mathrm{O}$ – any point at the surface of the earth;
- $\mathrm{x_e}$ axis - North direction;
- $\mathrm{y_e}$ axis - East direction;
- $\mathrm{z_e}$ axis - completes the right handed system (Gravity direction).

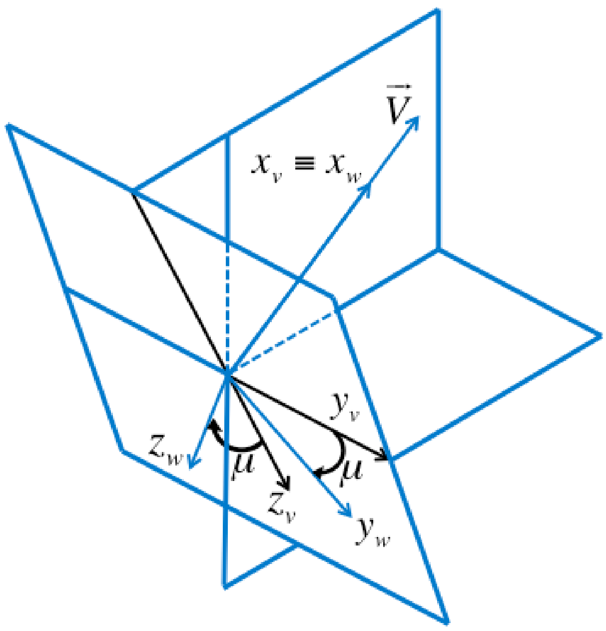


Figure 10: Aerodynamics forces

**Local horizon axes system** $(\mathbf{O}, \mathbf{x_h}, \mathbf{y_h}, \mathbf{z_h})$: Being the origin at the aircraft center of gravity, the axes move with the aircraft, but remain parallel to the ground.

- Origin: $\mathrm{O}$ – Aircraft center of gravity;
- $\mathrm{x_h}$ axis – parallel to $\mathrm{x_e}$;
- $\mathrm{y_h}$ axis - parallel to $\mathrm{y_e}$;
- $\mathrm{z_h}$ axis - completes the right handed system (Gravity direction).

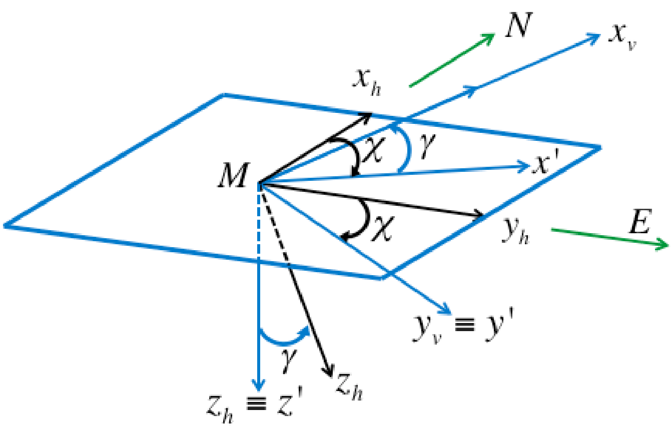


Figure 11: Local horizon axes system

**Local body axes system** $(\mathbf{O}, \mathbf{x_b}, \mathbf{y_b}, \mathbf{z_b})$: the axes are fixed to the aircraft.

- Origin: $\mathrm{O}$ – Aircraft center of gravity;

- $x_b$ axis – axis within the plane of symmetry of the aircraft, parallel to a reference line of the aircraft and with the direction of the aircraft movement.
- $y_b$ axis - axis with the right hand wind direction (completes the right handed system);
- $z_b$ axis - axis within the plane of symmetry of the aircraft, perpendicular to $x_b$ and with the direction of the bottom of the aircraft.

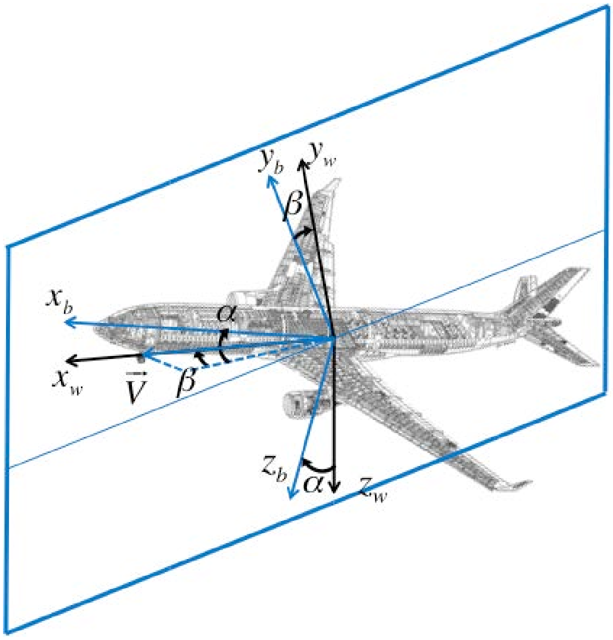


Figure 12: Local body axes system

**Wind axes system** $(\boldsymbol{O}, \boldsymbol{x_w}, \boldsymbol{y_w}, \boldsymbol{z_w})$**:** the axes are fixed to the aircraft.

- Origin: $O$ – Aircraft center of gravity;
- $x_w$ axis – axis with the direction of the aerodynamic velocity vector of the aircraft.
- $y_w$ axis - completes the right handed system;
- $z_w$ axis - axis within the plane of symmetry of the aircraft, perpendicular to $x_w$ and with the direction of the bottom of the aircraft.

The motion of the center of gravity of the aircraft is analyzed, which is under the influence of several forces. This motion is defined at each time by the position, velocity and mass of the aircraft (considered as a point mass). The aircraft is at any time, under the influence of gravitational (mg), aerodynamic (ç) and power plant forces ($F_T$).

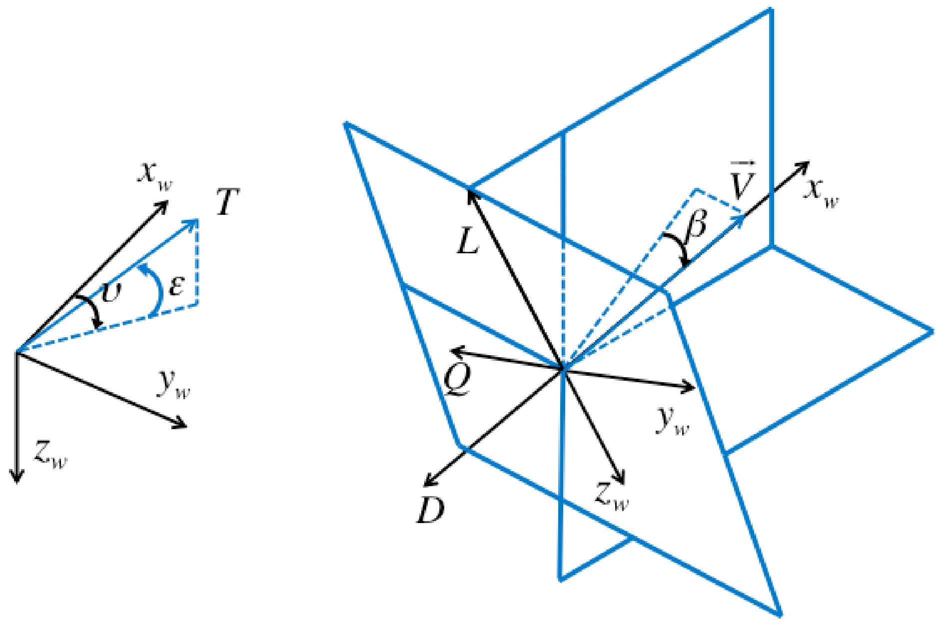


Figure 13: Wind axes system & thrust orientation

The analysis of airplane motion is performed through the usage of Newton's laws. Despite most aircraft structures are flexible, is assumed that the airplane is a rigid body. As a consequence, when the fuel is being consumed, the airplane is a variable-mass rigid body. It is important to highlight that in terms of aircraft motion, the earth is considered as an approximate inertial reference frame (aforesaid flat earth model) that leads to a small error in most analyses.

$$(\frac{d\vec{r}}{dt})_I = \vec{V}_I \tag{12}$$

$$m(\frac{d\vec{V}_I}{dt})_I = \vec{F}_A + \vec{F}_T + m\vec{g} \tag{13}$$

$$(\frac{dm}{dt})_I = -c \tag{14}$$

Where $\vec{\mathrm{r}} = \overrightarrow{\mathrm{OO_h}}$ is position vector, t the time, $\vec{\mathrm{V}}_{\mathrm{I}}$ is the absolute speed of the vehicle (absolute speed Earth-Centered Inertial system), $\mathrm{m}$ represents the mass of the vehicle and c is thee fuel-mass consumption; where the derivative of vector $\vec{\mathrm{r}}$ and $\vec{\mathrm{V}}_{\mathrm{I}}$ is taken at Earth-Centered Inertial axes system to obtain the scalar equations.

As a result, there is a set of 7 non-lineal ordinary differential equations that includes 3 components of vector associated with the position, velocity and mass. Aerodynamic and propulsion study allows the definition of $\vec{\mathrm{F}}_{\mathrm{A}}$, $\vec{\mathrm{F}}_{\mathrm{T}}$ and c. It is important to note that $\vec{\mathrm{V}}_{\mathrm{I}}$ is equal to ground speed $\vec{V}_g$ that could be defined as $\vec{V}_g = \vec{V} + \vec{V}_w$ where $\vec{V}$ is aerodynamic speed, and $\vec{V}_w$ is wind speed. Considering that there is no wind when $\vec{V}_I = \vec{V}_g = \vec{V}$.

### 3.6.3 Scalar equations

In order to derive the scalar equations, the set of equations on matrix form has to be considered. In this regard, the projection of vectors onto a particular axes system is necessary. Considering the following;

$$\vec{w} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{15}$$

and also

$$\vec{\vec{\Omega}} = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \tag{16}$$

it is possible to write,

$$\vec{w} \times \vec{a} = \vec{\vec{\Omega}} \cdot \vec{a} \tag{17}$$

therefore,

$$[\mathrm{A}]^E = [\Omega]^E \, [\mathrm{a}]^E \tag{18}$$

being,

$$[\Omega]^E = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \tag{19}$$

matrix associated to $\vec{\mathrm{w}}$.

### 3.6.4 Kinematic Equations

The first step is to obtain the set of scalar kinematic equations. For this step is necessary the projection of the equation vector onto the Earth-Centered Inertial axes system, the result is,

$$\left[\left(\frac{dr}{dt}\right)_I\right]^I = [V]^I \tag{20}$$

The set of scalar equations is obtained from the following,

$$[r]^I = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{21}$$

$$\left[\left(\frac{dr}{dt}\right)_I\right]^I = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{22}$$

$$[V]^W = \begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix} \tag{23}$$

$$[V]^I = [T]^{HW}[V]^W = \begin{bmatrix} V\cos\gamma\cos\chi \\ V\cos\gamma\sin\chi \\ -V\sin\gamma \end{bmatrix} \tag{24}$$

Being $[\mathrm{T}]^{\mathrm{HW}}$ the transpose matrix of $[\mathrm{T}]^{\mathrm{WH}}$. Therefore, the set of kinematic equations considering $\mathrm{h} = -\mathrm{z}$ is;

$$\begin{gathered} \frac{dx}{dt} = V\cos\gamma\cos\chi \\ \frac{dy}{dt} = V\cos\gamma\sin\chi \\ \frac{dh}{dt} = V\sin\gamma \end{gathered} \tag{25}$$

### 3.6.5 Dynamic Equations

Dynamic Equations is used to derive the differential equations for which define the velocity vector of the airplane center of gravity relative to the ground, the axis wind system. Considering two reference axis systems, fix (F) and mobile (M) with a constant angular speed $\vec{\mathrm{w}}_{\mathrm{MF}}$. The relation between the temporal derivate of a vector $\vec{\mathrm{A}}$ at both reference axis systems by:

$$\left(\frac{d\vec{A}}{dt}\right)_F = \left(\frac{d\vec{A}}{dt}\right)_M + \vec{w}_{MF} \times \vec{A} \tag{26}$$

therefore, taking into account that,

$$\left(\frac{d\vec{V}}{dt}\right)_I = \left(\frac{d\vec{V}}{dt}\right)_W + \vec{w}_{WI} \times \vec{V} \tag{27}$$

the following can be obtained,

$$\left(\frac{d\vec{V}}{dt}\right)_I + \vec{w}_{WI} \times \vec{V} = \frac{1}{m}\overrightarrow{F_{A,T}} + \vec{g} \tag{28}$$

the following is the dynamic vector equation projected at wind axis reference system;

$$\left[\left(\frac{dV}{dt}\right)_W\right]^W + [\Omega_{WH}]^W[V]^W = \frac{1}{m}\left[F_{A,T}\right]^W + [g]^W \tag{29}$$

where $[\Omega_{WH}]^W$ is the matrix associated to $\vec{w}_{WH} = \vec{w}_{WI}$ that is given by;

$$\vec{w}_{WI} = \dot{\chi}\overrightarrow{k_h} + \dot{\gamma}\overrightarrow{J_x} + \dot{\mu}\overrightarrow{\iota_w} \tag{30}$$

Being $\overrightarrow{J_x}$ direction $y'$ of intermediate axis $X'$ that is obtained when rotating $H$ axis by angle $\chi$ looking toward the $z_h$ axis. Thus, scalar equations are obtained from the following expressions:

$$\left[\left(\frac{dV}{dt}\right)_W\right]^W = \begin{bmatrix}\dot{V}\\0\\0\end{bmatrix} \tag{31}$$

$$[g]^H = \begin{bmatrix}0\\0\\g\end{bmatrix} \tag{32}$$

$$[g]^W = [T]^{WH}[g]^h = \begin{bmatrix}-g\sin\gamma\\g\cos\gamma\sin\mu\\g\cos\gamma\cos\mu\end{bmatrix} \tag{33}$$

$$[\Omega_{WH}]^W[V]^W = \begin{bmatrix}0\\V(\dot{\chi}\cos\gamma\cos\mu - \dot{\gamma}\sin\mu)\\-V(\dot{\chi}\cos\gamma\sin\mu - \dot{\gamma}\cos\mu)\end{bmatrix} \tag{34}$$

And finally, the result is the following;

$$\begin{gathered}\frac{dV}{dt} = \frac{1}{m}(F_{A,T})_{x_w} - g\sin\gamma\\V(\frac{d\chi}{dt}\cos\gamma\cos\mu - \frac{d\gamma}{dt}\sin\mu) = \frac{1}{m}\left(F_{A,T}\right)_{y_w} - g\cos\gamma\sin\mu\\-V(\frac{d\chi}{dt}\cos\gamma\sin\mu - \frac{d\gamma}{dt}\cos\mu) = \frac{1}{m}\left(F_{A,T}\right)_{z_w} - g\cos\gamma\cos\mu\end{gathered} \tag{35}$$

where $(\mathrm{F}_{\mathrm{A,T}})_{\mathrm{x_w}}$, $(\mathrm{F}_{\mathrm{A,T}})_{\mathrm{y_w}}$ and $(\mathrm{F}_{\mathrm{A,T}})_{\mathrm{z_w}}$ are the components of aerodynamic and propulsion forces by wind axes.

Combining the second and third equation from the previous equations, the result is the following set of equations;

$$\begin{aligned} \frac{dV}{dt} &= \frac{1}{m}(F_{A,T})_{x_w} - g\sin\gamma \\ V\cos\gamma\frac{d\chi}{dt} &= \frac{1}{m}\left[(F_{A,T})_{y_w}\cos\mu - (F_{A,T})_{z_w}\sin\mu\right] \\ -V\frac{d\gamma}{dt} &= \frac{1}{m}\left[(F_{A,T})_{z_w}\sin\mu + (F_{A,T})_{z_w}\cos\mu\right] + g\cos\gamma \end{aligned} \tag{36}$$

### 3.6.6 General Equations

Aerodynamic and Propulsive forces at wind axes are given by the following;

$$[F_{A,T}]^W = \begin{bmatrix} T\cos\varepsilon\cos\nu - D \\ T\cos\varepsilon\sin\nu - Q \\ -(L + T\sin\varepsilon) \end{bmatrix} \tag{37}$$

Therefore, considering the assumptions above, the set of general equations is as follows;

$$\begin{aligned} \frac{dx}{dt} &= V\cos\gamma\cos\chi \\ \frac{dy}{dt} &= V\cos\gamma\sin\chi \\ \frac{dh}{dt} &= V\sin\gamma \\ m\frac{dV}{dt} &= T\cos\varepsilon\cos\nu - D - mg\sin\gamma \\ V\cos\gamma\frac{d\chi}{dt} &= (T\cos\varepsilon\sin\nu - Q)\cos\mu + (L + T\sin\varepsilon)\sin\mu \\ mV\frac{d\gamma}{dt} &= -[(T\cos\varepsilon\sin\nu - Q)\sin\mu - (L + T\sin\varepsilon)\cos\mu] - mg\cos\gamma \\ \frac{dm}{dt} &= -c \end{aligned} \tag{38}$$

Within this general set of equations, there are the following functional dependencies;

$$
\begin{gathered}
L = L\ (h, V, \propto, \beta) \\
D = D\ (h, V, \propto, \beta) \\
Q = Q\ (h, V, \propto, \beta) \\
T = T(h, V, \pi) \\
c = c\ (h, V, \pi) \\
\varepsilon = \varepsilon\ (\alpha, \beta) \\
\nu = \nu\ (\alpha, \beta)
\end{gathered} \tag{39}
$$

Where π is the control parameter for the engine. Thus, a set of seven (7) ordinary differential equations with 11 dependent variables; 7 state variables (derivative variables), $x$, $y$, $h$, $V$, $\chi$, $\gamma$, $m$; and 4 control variables (non-derivative variables) $\alpha$, $\beta$, $\pi$, $\mu$. Thus, there are 4 Degree of Freedom (DOF), in other words 4 additional conditions needs to be specified in order to solve the set of equations along with the initial conditions.

In order to obtain angles ε and ν is necessary to consider thrust orientation by local body axes system, which is known. Being $\vec{\mathrm{T}} = \mathrm{T}\vec{\mathrm{t}}$, where;

$$
[t]^B = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} \tag{40}
$$

And $\mathrm{k}_1$, $\mathrm{k}_2$, $\mathrm{k}_3$ are such as ${\mathrm{k}_1}^2 + {\mathrm{k}_2}^2 + {\mathrm{k}_3}^2 = 1$. The components of $\vec{\mathrm{t}}$ are as follows;

$$
[t]^W = \begin{bmatrix} \cos\varepsilon \cos\nu \\ \cos\varepsilon \sin\nu \\ -\sin\varepsilon \end{bmatrix} \tag{41}
$$

From the following;

$$
[t]^B = [T]^{BW}[t]^W \tag{42}
$$

Is possible to obtain $\varepsilon = \varepsilon\ (\alpha, \beta)$ and $\nu = \nu\ (\alpha, \beta)$;

$$
\begin{gathered}
\sin\varepsilon = \ k_1 \sin\alpha - k_3 \cos\alpha \\
\cos\varepsilon \sin(\beta + \nu) = \ k_2
\end{gathered} \tag{43}
$$

### 3.6.7 Symmetric flight

It is assumed that the flight is symmetric when $\vec{V}$ and $\vec{T}$ is within the plane of symmetry and $Q = 0$. As a consequence, the following takes place $\beta = \nu = k_2 = 0$. The set of equations for symmetric flight are therefore;

$$
\begin{aligned}
\frac{dx}{dt} &= V\cos\gamma\cos\chi \\
\frac{dy}{dt} &= V\cos\gamma\sin\chi \\
\frac{dh}{dt} &= V\sin\gamma \\
m\frac{dV}{dt} &= T\cos\varepsilon - D - mg\sin\gamma \\
V\cos\gamma\frac{d\chi}{dt} &= (L + T\sin\varepsilon)\sin\mu \\
mV\frac{d\gamma}{dt} &= (L + T\sin\varepsilon)\cos\mu - mg\cos\gamma \\
\frac{dm}{dt} &= -c
\end{aligned}
\tag{44}
$$

Within this general set of equations, there are the following functional dependencies;

$$
\begin{aligned}
L &= L\,(h, V, \propto) \\
D &= D\,(h, V, \propto) \\
Q &= Q\,(h, V, \propto) \\
T &= T(h, V, \pi) \\
c &= c\,(h, V, \pi) \\
\varepsilon &= \varepsilon\,(\alpha)
\end{aligned}
\tag{45}
$$

Thus, a set of seven (7) ordinary differential equations with 10 dependent variables; 7 state variables (derivative variables), $x$, $y$, $h$, $V$, $\chi$, $\gamma$, $m$; and 3 control variables (non-derivative variables) $\alpha$, $\pi$, $\mu$. Thus, there are 3 Degree of Freedom (DoF), in other words, 3 additional conditions needs to be specified in order to solve the set of equations along with the initial conditions.

For symmetric flight, the following takes place;

- plane by $x_w$ and $y_w$ of the wind axis system is the same as the symmetric plane of the aircraft,
- axis $y_w$ and $y_b$ have the same direction,

- $\alpha$ is the angle between $x_b$ and $\vec{V}$, and
- $\varepsilon$ is the angle between $\vec{T}$ and $\vec{V}$.

In this case,

$$\begin{bmatrix} k_1 \\ 0 \\ k_3 \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\varepsilon \\ 0 \\ -\sin\varepsilon \end{bmatrix} \tag{46}$$

Where the following is obtained;

$$\varepsilon = \alpha - artan\,\frac{k_3}{k_1} \tag{47}$$

And therefore;

$$\varepsilon = \alpha + \varepsilon_0 \tag{48}$$

Being $\varepsilon_0$ a known parameter.

### 3.6.8 Symmetric flight within a vertical plane

In general, the velocity vector is commonly oriented relative to the body axes by the sideslip angle and the angle of attack. In case the velocity vector is in the plane of symmetry of the airplane, the sideslip angle is zero ($\chi = 0$) and thus, such flight is called symmetric. For symmetric flight over flat earth, the equations of motion are given by;

$$\begin{aligned} \frac{dx}{dt} &= V\cos\gamma \\ \frac{dh}{dt} &= V\sin\gamma \\ m\frac{dV}{dt} &= T\cos\varepsilon - D - mg\sin\gamma \\ mV\frac{d\gamma}{dt} &= L + T\sin\varepsilon - mg\cos\gamma \\ \frac{dm}{dt} &= -c \end{aligned} \tag{49}$$

Thus, a set of five (5) ordinary differential equations with 7 dependent variables; 5 state variables (derivative variables), x, h, V, γ, m; and 2 control variables (non-derivative variables) α, π. Thus, for symmetric flight there are 2 Degree of Freedom (DOF), in other words 2 additional conditions needs to be specified in order to solve the set of equations along with the initial conditions.

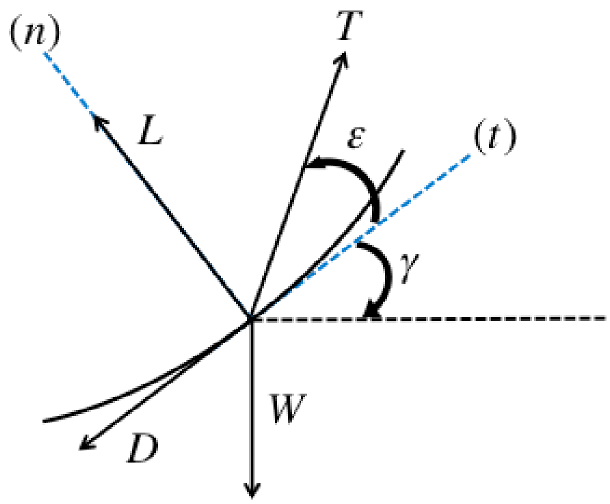


Figure 14: Symmetric flight within a vertical plane

### 3.6.9 Aircraft performance - equations of motion for the problem

The considered representation of the aircraft that has been considered within this dissertation is a dynamic model, which represents the point variable mass motion over a spherical flat non-rotating earth model besides neglecting wind components. The resulting set of differential equations of the aircraft is the following:

$$\dot{x} = V.\cos(\gamma) \tag{50}$$

$$\dot{h} = V.\sin(\gamma) \tag{51}$$

$$\dot{V} = \frac{T(h,V) - D(h,V,C_d) - m.g.\sin(\gamma)}{m(t)} \tag{52}$$

$$\dot{\gamma} = \frac{L(h,V,C_l) - m.g.\sin(\gamma)}{m(t).V(t)} \tag{53}$$

$$\dot{m} = -T(h,V).\eta(h,V) \tag{54}$$

where the state vector is comprised of the true airspeed $V$, the longitudinal position $x$, the aerodynamic flight path angle $\gamma$, the altitude $h$ and the mass of the aircraft $m$. In addition to the states, there are other components like $T$, which represent the thrust, $g$ the gravity acceleration (assumed as a constant value), $D$ is the aerodynamic drag and, $\eta$ is the thrust specific fuel flow.

In terms of the atmosphere, it has been considered the ICAO Standard Atmosphere (ISA) model [37], which presents pressure $p(h)$, density $\rho(h)$ and temperature $\tau\,(h)$. This model denotes $p_0$, $\rho_0$ and $\tau_0$ for the standard values at sea level for pressure, density and temperature respectively.

# 4 Multi-factor Optimization

The aim of this chapter is to present the factors that have been considered within the presented methodology for the optimization problem of this dissertation. Is important to note that despite there is an environmental aspect associated to both of them, one implies economical connotation, as its savings will affect the cost of operation of an aircraft.

## 4.1 Noise factor

Over the past few years, several dissertations have tackled the challenges of optimizing the noise annoyance impact in the human activities of airport neighbors; [15][38][39][40]. The evidences of this statement are the significant number of published noise annoyance models that goes from a simplistic deterministic model to the most sophisticate methods.

Modeling aircraft noise has been recognized as a global priority with the objective of providing reliable aircraft noise prediction tools. Despite the variety of theoretical methods for predicting aircraft method relying on physical model of noise production and propagation, those semi-scientific methods based on certain empiricism have gained better acceptance by industry, airports and aviation regulators.

As a result of the need for reliable noise prediction within the civil aviation sector, Federal Aviation Authority (FAA) promoted in 1978 the Integrated Noise Model (INM) [41]. INM is a software tool, which provides an application fed by a small set of inputs, with the objective of determining aircraft noise in the vicinity of airports and the impacts on surrounding areas. In order to gain further insights of INM models please see [42], where the reader will find a detailed description of how INM models aircraft noise as well as computation of several metrics from the INM technical manual.

The noise model utilized on this dissertation is based on the methodology employed by the INM, which has been adopted as the standard package for noise evaluations in several countries. There exist several metrics when aircraft noise is studied. Experts in acoustics considering the human sensitivity to the frequencies can propose the weighting scales.

The core of this methodology relies on an acoustic database of noise versus thrust distance, Noise-Power-Distance (NPD). Noise levels are calculated at a particular point through interpolation of noise values obtained from a NPD database. This data, which is based on empirical measurement for each aircraft type, is collected on the table whose values are A-weighted decibel levels for the different combination of distance and thrust. The maximum A-weighted sound level $L_{max}$ has been considered as the metric throughout this investigation. It is out of the scope this thesis to perform an accurate study at a specific time period. Noise levels in the tables assume a standard reference day conditions (temperature of $27^0C$, pressure of $1{,}013$ hPa and $70\%$ relative humidity and altitude of mean sea level). Within INM model, there are attenuation adjustments for the computation of maximum noise level metrics that are categorized within atmospheric absorption adjustment, acoustic impedance adjustment and lateral attenuation adjustment.

In order to compute the noise levels at a given point, it is necessary to interpolate the empirical NPD values. Moreover, in order to obtain noise levels, which lie between the specified values included in the NPD table, it has been necessary to utilize linear interpolation on engine thrust settings (pp) and logarithmic interpolation on altitude (h). These calculations have been performed through Curve Fitting Toolbox from Matlab.

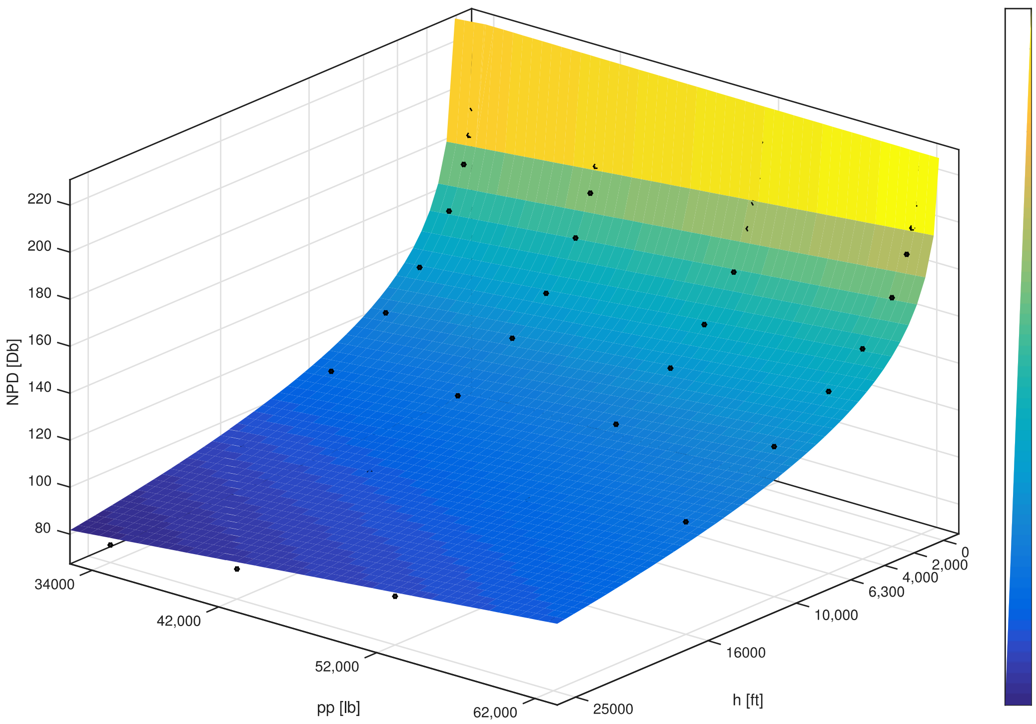


Figure 15: NPD ($L_{max}$) vs engine thrust settings (pp), altitude (h)

## 4.2 Fuel consumption factor

Comparing with the electricity generation, road transport, and even cement making, aviation is not one a huge source of man-made emissions. But it is a source that is growing fast according to the traffic forecasts. More efficient engines and the introduction of a certain amount of electrification will certainly help. Towards zero emissions, every little helps and any potential reduction of fuel consumption and thus generation of greenhouse-gas emissions will help on cutting into the expected growth rate.

The operating cost of an aircraft is subject to fixed and variable factors, which are highly dependent to the aircraft operation. As a performance related component, the consumed amount of fuel is a prominent criteria on optimization of aircraft operations. An interesting study regarding effects on fuel consumption was presented by Turgut et al. on [43]. Besides, the air quality has an important impact on global climate change and the assessment of the impact of air pollutant must not be avoided. There exist several computer databases to quantify the gaseous emissions. One of the most relevant methods for emissions calculations is Boeing Method 2 Fuel Flow Methodology,[44]. Chen applied this methodology with the aim of estimating the fuel consumption and the resulting aviation emissions in the en-route airspace [45]. Boeing Method 2 Fuel Flow Methodology is an enhanced version of the previous one named "Boeing Fuel Flow Method 1"[46]. The main difference is the correction equations for fuel flow and emission indices, which considers ambient temperature, pressure, humidity and Mach number. Emissions factor is of paramount importance and has been extensively across the transportation realm. Despite the continuous effort on emission calculations, Hartjes concluded on [15] that the optimization in terms of gaseous pollutants did not led to significant results. Therefore, considering the direct coupling between emissions and fuel burn, the latter has been considered on this study as the environmental criteria for the calculations.

## 4.3 Optimization criteria

The environmental optimization criteria have been modeled considering two magnitudes; maximum A-weighted sound level ($\mathrm{L_{max}}$) and fuel burn. Aiming at supporting this multi-objective optimization, the weighted combination of the aforementioned factors have been implemented as follows,

$$J = a.Noise + b.Fuel\ consumption \quad (55)$$

Where a & b are adjustable weighting constants. The values of these constants are directly related to the trade-off between noise exposure and fuel consumption. Both factors can receive the same weighting avoiding the precedence of one of them.

### 4.4 Pareto frontier

A solution of the optimization problem is said to be Pareto optimal (or Pareto frontier). In mathematical terms, every Pareto optimal solution is an equally acceptable solution of the optimization problem. However, it is highly recommended to select one point as a solution. The selection of one out of the set of Pareto optimal solutions brings the opportunity to influence in the decision making of what needs to be prioritized at a particular scenario and is not a straightforward task. Selecting a Pareto optimal is linked to the environment of the scenario that is subject to be studied as well as the operational needs.

The priorities of the objectives are reflected by the weights of the constants, which are real numbers and normalized. The decision makers will have the capability to adjust the weighting of the constants. It is out of the scope to evaluate the decision-making on the most suitable Pareto frontier for a particular TMA. In order to facilitate the discussion, consider the new formulation of the aforesaid equation where $k$ is equal to $a/b$.

$$J' = Fuel\ Consumption + k.\sum_{i}^{n} Noise \quad (56)$$

The diagram represents the effects of the weights of the constant $k$, in terms of noise and fuel-consumption for the optimized CCOs. It can be appreciated that with higher weights for $k$, the importance of Noise factor increases, the solutions of the optimization problem presents higher values of fuel consumption and therefore lower fuel savings.

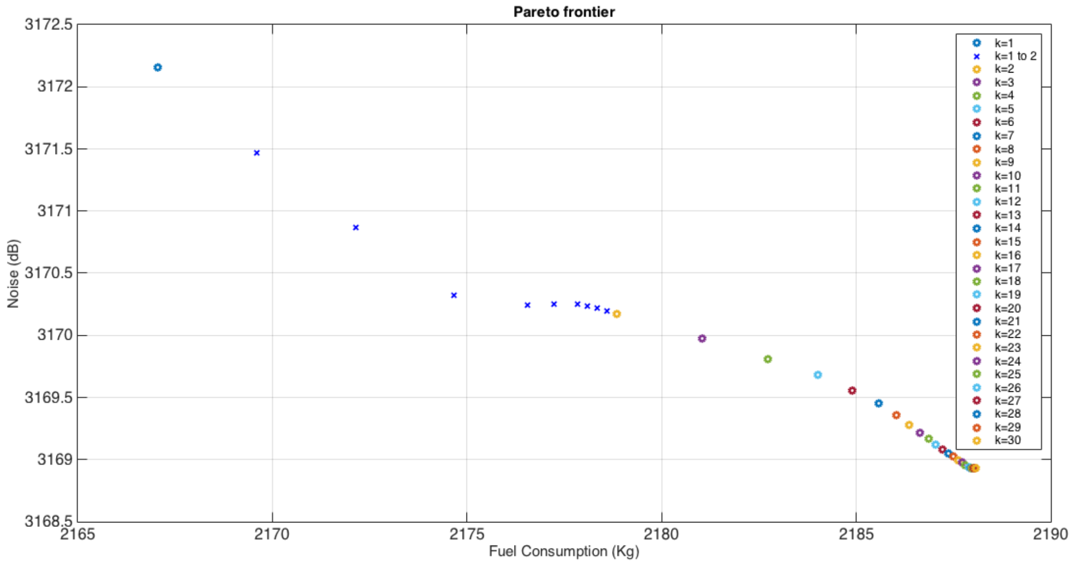


Figure 16: Pareto frontier in terms of Noise (dB) and Fuel Consumption (Kg)

## 4.5 Case study for the enhancement of operational efficiency of terminal maneuvering areas through continuous climb operations

Efficient continuous departure is an operational solution supported by global air navigation initiatives for future Air Traffic Management. In an effort to contribute for sustainable aviation, the following aims at presenting the efficiency enhancements at terminal airspace operation through the multi-objective trajectory optimization of flight departures. This put in place consolidated multi-objective models in terms of noise and fuel consumption for the calculations of optimized aircraft trajectories based on CCOs principles.

### 4.5.1 Case study

#### *4.5.1.1 Departures at Adolfo Suárez Madrid Barajas*

Adolfo-Suárez Madrid Barajas is the largest airport in Spain with 409,832 total operations in 2018. Considered as one of the largest airport in Europe by physical size, it is the country's busiest airport in Spain, and Europe's sixth busiest. The airport is predominantly operated in North configuration and runway (RWY) 36L was selected as the preferred option for this study. In particular, the chosen flight segments go from ground to waypoint (WPT) AVILA.

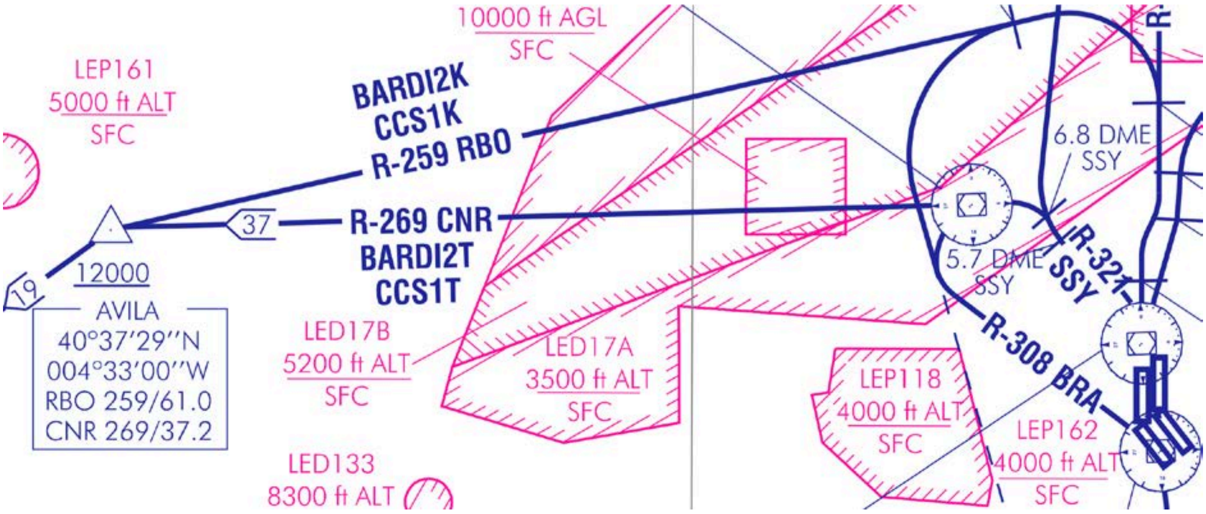


Figure 17: SIDs RWY 36L: Detailed view of selected flight segments associated to BARDI2T/ CCS1T & BARDI2K/CCS1K SIDs

The figure above shows a zoom view of the published chart, which includes the SIDs for RWY 36L, usable at daytime. SIDs BARDI TWO TANGO (BARDI2T) & CÁCERES ONE TANGO (CCS1T), are only allowed to authorized aircraft and thus, BARDI TWO KILO (BARDI2K) SID & CÁCERES ONE KILO (CCS1K) SID become mandatory to listed aircraft due to noise restrictions. Published noise abatement procedures are applicable to all take-offs, unless exceptionally cancelled due to an event that cannot be reasonably anticipated. The facilitation of CCO when performing these departure segments must satisfy the airspace restrictions and operational constraints. The BARDI2K/CCS1K SID corresponds to the tackled departure flight segment.

#### *4.5.1.2 Operational constraints*

The complexity of the problem is higher when applied to a real environment due to the necessary compliance of operational constraints. The initial conditions on the studied procedure are taken from ground. Is important to note that the departure segment before attaining 1000ft altitude is operationally restrictive and there are no many degrees of freedom for a potential optimization.

Table 1: Boundary conditions

| Variables and states | Initial values | Final values |
|---|---|---|
| Distance s [Nm] | 0 | $s_f$ |
| Time t [s] | 0 | Unconstrained |

| | | |
|---|---|---|
| Velocity V [Kt] | $V_i$ | $V_f$ |
| Altitude h [ft] | 0 | $h_f$ |
| Rate of Climb ROC [fpm] | 0 | Unconstrained |
| Flight path angle $\gamma$ [rad] | 0 | Unconstrained |
| Thrust Level Percentage (TLP) [0-1] | 0.8 | Unconstrained |
| Gross Weight [Kg] | M1 | Unconstrained |

The CCO was modeled enforcing the boundary conditions described on the indicated table. In terms of speed; No deceleration was permitted, as this is the trend observed in actual data. The initial climb speed corresponds to the sample mean of the analyzed FDR data. The final climb speed has been set according to the data analyzed. Analytics of real departures for this specific scenario unmasked a typical operational constraint for departures. This operational constraint refers to the limitation of 250 Kt. below FL 100 [19]. In this regard, the optimization of this departure has been forced to comply with this operational limitation up to the crossover altitude.

#### *4.5.1.3 Numerical results*

Once the CCOs are optimized, it is of paramount importance to compare the optimized departure against the conventional departure. In this case, we have selected a historic actual aircraft with a representative value regarding the actual Take-off Weight considering the FDR database. In other words, the stored database includes a different variety of actual operational Take-off Weights, and the selected one is illustrative. Unfortunately, the value of this parameter has not been disclosed in purpose. This actual conventional departure is also consistent in terms of level-off segments and do not present significant level-off segments, particularly at low level altitudes. This actual departure corresponds to a departure trajectory operated in North configuration and runway (RWY) 36L and SID BARDI2K/CCS1K.

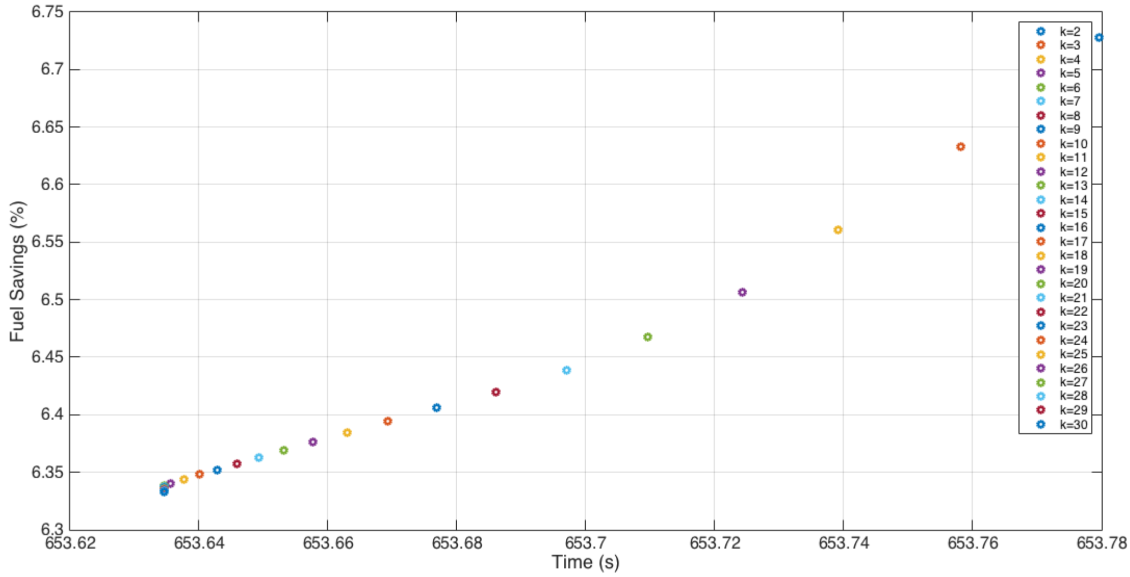


Figure 18 : Conventional departure compared to Optimized CCO - Fuel Savings (%) vs. Time (s)

The fig.16 gathers the information regarding the Fuel Savings (%) versus the time required to perform the optimal CCO. The values regarding the fuel savings represent the reduction of fuel consumption when comparing the optimal CCO against the actual departure. The effects of the constant value "k" can be appreciated and the higher is the weight of the noise (higher k), the lower is the time required. It can be observed that the fuel savings achieved goes between 6.3% and 6.75%. Thus, considering the time requirements and fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

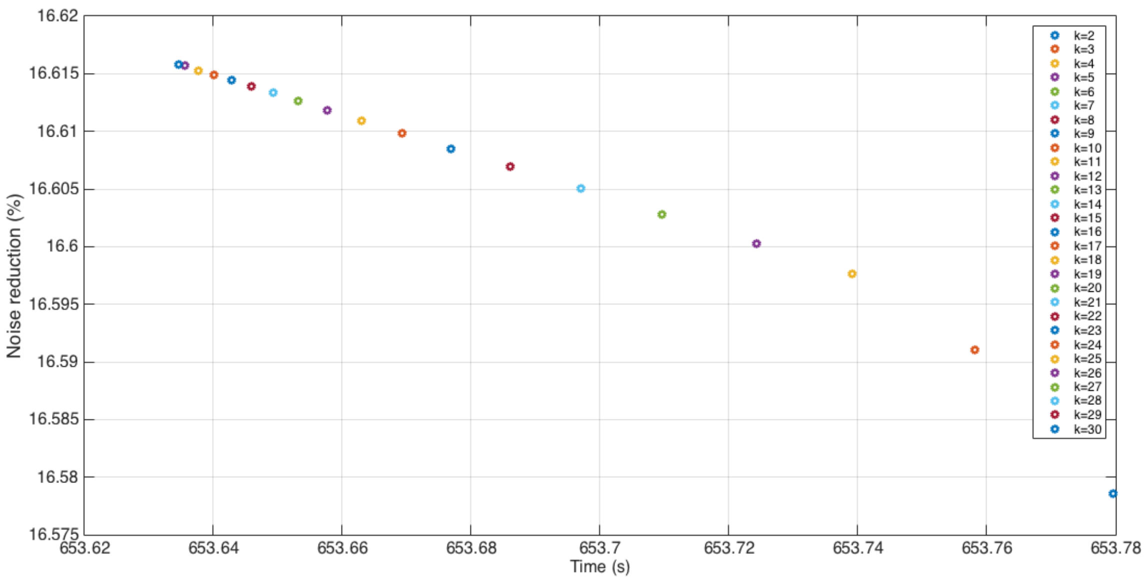


Figure 19: Conventional departure compared to Optimized CCO – Noise reduction (%) vs Time (s)

The fig.17 includes the information regarding the Noise reduction (%) versus the time required to perform the optimal CCO. The values regarding the fuel savings represent the reduction of noise when comparing the optimal CCO against the actual departure. The effects of the constant value “k” can be appreciated and the higher is the weight of the noise (higher k), the higher is the time required. It can be observed that the noise reduction achieved goes between 16.58% and 16.61%. Thus, considering the time requirements and fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

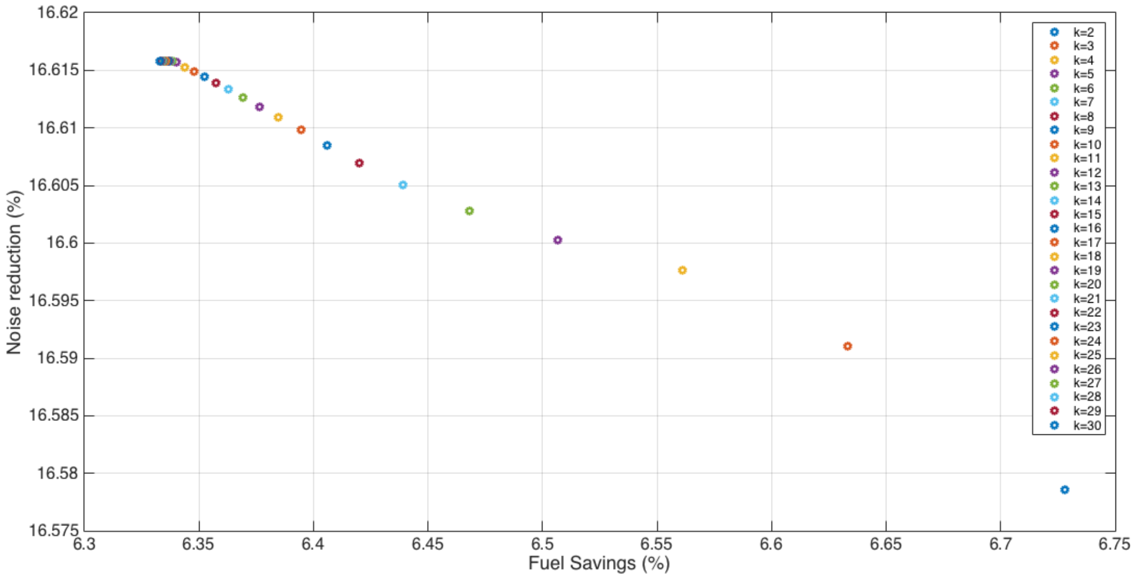


Figure 20: Conventional departure compared to Optimized CCO - Noise Reduction (%) vs. Fuel Savings (%)

The Fig.20 reveals the information regarding the Noise reduction (%) versus Fuel Savings (%) between optimal CCOs and the actual conventional departure. The effects of the constant value “k” can be appreciated and the higher is the weight of the noise (higher k), the higher is the noise reduction and the lower is the fuel savings achieved and in case of lower k, the higher fuel savings and lower noise reduction will be obtained. This is due to the fact that the represented when noise reduction is a priority, the aircraft tends to climb earlier that presents inefficiencies in terms of fuel consumption. Contrariwise, in case the priority is to reduce fuel consumption, aircraft tends to increase to a velocity that allows performing the optimal vertical climb strategy. Thus, considering the time and noise requirements along with the priorities for fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

#### 4.5.1.4 *Conclusions regarding the enhancement of operational efficiency of terminal maneuvering areas through continuous climb operations*

In view of the results when comparing a conventional departure versus an optimized CCO in terms of noise and fuel consumption brings benefits when integrated at terminal airspace operation through trajectory optimization by means of Chebyshev-Gauss-Lobatto (CGL). The application of a consolidated mathematical method was not only applied to multiple operational factors but also reflected restrictions of actual Air Traffic Control (ATC) operational constraints.

Unlike Standard Arrival Routes where aircraft are tactically guided by air traffic controllers, SID routes tend to follow fixed flight paths. Thus, the optimization of the vertical profile may be considered as an appropriate initiative for departure efficiency.

The benefits are presented through 6.3% - 6.75% of fuel savings 16.6% of noise reductions for the studied flight segment when comparing an optimized CCO with a representative actual departure. These results bear out the advantages to the communities around the airports when optimized CCOs are facilitated by ATC.

From operational point of view, facilitating uninterrupted climb flight operation allowing the aircraft to attain initial cruise flight level at an optimum air speed with optimal thrust settings will lead to more consistent flight paths whilst reducing the number of required radio transmissions. As a consequence, this may be traduced on lower pilot and air traffic controller workload.

This reinforces the idea of transmitting the importance of CCOs and furthermore, promotes the usage of this operating technique in TMAs.

# 5 Environmental benefits in terms of fuel efficiency and noise when introducing continuous climb operations as part of terminal airspace operation

In view of the results from the main chapter, the main driver within this chapter is to gain further insights about the environmental realities of enhancing departure aircraft procedures, based on optimal Continuous Climb Operations (CCOs), for a long-range wide-body aircraft. The findings are driven by the advantage offered by the analysis of real Flight Data Recorder (FDR) data against the simulated data, obtained through the use of orthogonal polynomials such as Chebyshev polynomials, in partnership with Gauss-type integration rules. Therein, the calculation of improved trajectories aims at reducing the negative environmental aspects of civil aviation on urbanized areas around airports and at enhancing the operational cost efficiency. The Multi-Objective trajectory optimization was not only applied to multiple environmental factors particularly; fuel consumption and noise impacts, but also was constrained by Air Traffic Control (ATC) operational restrictions from a real scenario. The problem, tackled through a multi-objective optimization process based on CCO principles by a Chebyshev-Gauss-Lobatto (CGL) Pseudospectral Method, relies on a numerical framework that bears out the benefits in terms of fuel consumption and noise emissions. Therefore, this study promotes the need for investigating, not the implementation of a CCO generally assumed as an uninterrupted climb departure, but an optimal CCO.

## 5.1 Case study

Limited research has been conducted in terms of "pure" CCOs, as the benefits did not seem to be noteworthy. Nonetheless, considering during climb phase engines usually run close to full throttle, there are enough potential for reducing the environmental footprint in living areas around the airports.

The successful application of a CCO implies the optimal climb departure according to factors like; aircraft, airport, runway, Standard Instrument Departure (SIDs)… Below, an assessment of the optimal CCOs for the departure flights at one of the busiest airports in Spain is presented. It covers the enhancements of Airbus A330 departures for a variety of operational Take-Off Weights that represent the real operations. The exhaustive analysis of real FDR data supported this investigation allowing among others, the identification of real boundary conditions and constraints. This data source is a valuable tool, which provides accurate information based on the measured parameters.

The trade-off between noise impact and fuel consumption affects the vertical path. In this chapter, the vertical flight profile has been modeled considering the flight characteristics, limitations and capabilities of aircraft A330 performing an optimized CCO.

The mathematical method that was used is based on optimal control theory, which aims at determining the control input that will cause a system to achieve the control objectives, while satisfying the constraints and also optimizing some performance criterion. For this problem, the trajectory optimization problem is solved following an open loop terminal control problem that allows the constraints acting on the dynamical system to be considered in a way that the optimized trajectory will be admissible.

## 5.2 Methodology

The previously described trajectory optimization problem has been solved through Chebyshev Pseudospectral Method. This method was hand-tailored and implemented in AMPL modeling language [35], for an Airbus A330 aircraft using IPOPT as NLP solver. For the sake of clarity, AMPL is an algebraic modeling system for mathematical programming of large-scale optimization problems. A solver is defined as the number-crunching algorithm that computes optimal solutions.

Several features characterize the modeling of a CCO; To begin with, the algorithm, for a given length, has to provide the most beneficial departure. In this regard, leveled segments do not take place which means the nature of a continuously climbing path is being respected ensuring no level-offs segments. Additionally, this method of operation allows the aircraft to climb at optimum air speed and engine thrust settings. Accordingly, the model has to determine the most convenient thrust settings as a result of a trade-off between noise and fuel consumption, considering the effects of the altitude. Despite the fact the air speed has been modeled following the same approach, ATC constraints may have effect on its evolution.

The AMPL self-implemented optimization model is supported by the latest Base of Aircraft DAta (BADA 4.1 [36]). BADA is an Aircraft Performance Model applicable for aircraft trajectory simulation and prediction within the domain of Air Traffic Management. This model adopted by BADA is based on a mass-varying, kinetic approach. This approach models an aircraft as a point and requires modeling of underlying forces for aircraft motion. The AMPL optimization model has been validated according to real data extracted from A330 FDR. This process has been performed through the analysis of the vertical profiles as well as the evolution of key performance parameters of the simulated environment against FDR data. This validation provides accurate performances and realistic results when performing simulations of aircraft operations for this aircraft type. The optimization has been applied to five representative operational Gross Weight (GW) values presented on the table below covering thus, its operational variability. This allows evaluation of the potential impacts for different Gross Weight values when performing an optimal CCO considering noise and fuel burn.

Table 2: Gross Weights

| Aircraft | M1 | M2 | M3 | M4 | M5 |
|---|---|---|---|---|---|
| Gross Weight [Kg] | 198800 | 204800 | 211100 | 213100 | 219400 |

The overall process could be simplistically summarized in two main steps; Validation and Optimization. The first step, validation centered process in order to show whether the simulation of departure trajectories were compliance with the real departures or not. This exercises implied the analysis and monitoring activities of several key indicators, among others; thrust settings, velocity, altitude, distance and time.

Once the reference scenario was established and the model was validated, the second step was launched in order to achieve the optimization of the departure vertical profile. It was comprised by the establishment of constraints and boundary conditions and settled the test-bed for the simulations.

## 5.3 Operational constraints and boundary conditions

The complexity of the problem is significantly higher when applied to a real environment due to the necessary compliance of operational constraints. The initial conditions on the studied procedure are taken from ground. Is important to note that the departure segment before attaining 1000 ft altitude is operationally quite restrictive and there are no many degrees of freedom for a potential optimization. Besides, within the realm of the operational constraints, the obstacle clearance must be respected for the entire trajectory. Particularly for this scenario, the minimum altitude is 3500ft at 15 Nm.

Table 3: Boundary conditions

| Variables and states | Initial values | Final values |
|---|---|---|
| Distance s [Nm] | 0 | $S_f$ |
| Time t [s] | 0 | Unconstrained |
| Velocity V [Kt] | $V_i$ | $V_f$ |
| Altitude h [ft] | 0 | $h_f$ |
| Rate of Climb ROC [fpm] | 0 | $ROC_f$ |
| Flight path angle $\gamma$ [rad] | 0 | $\gamma_f$ |
| Thrust Level Percentage (TLP) [0-1] | 0.8 | Unconstrained |
| Gross Weight [Kg] | M1 / M2 / M3 / M4 / M5 | Unconstrained |

The CCO was modeled enforcing the boundary conditions described on table above. In terms of speed; No deceleration was permitted, as this is the trend observed in real data. The initial climb speed corresponds to the sample mean of the analyzed FDR data, which is also aligned with the recommendation from the NADPs [14]. The final climb speed has been set according to the data analyzed. Analytics of real departures for this specific scenario unmasked a typical operational constraint for departures. This operational constraint refers to the limitation of

250Kt below FL 100 [14]. In this regard, the optimization of this departure has been forced to comply with this operational limitation up to the crossover altitude. Certain length and target altitude characterize the considered departure according to FDR data analytics.

## 5.4 Numerical results

This section gathers the numerical results obtained after determining the most efficient CCO for a given mass, by a CGL Pseudospetral Method. As concluded on [33]; this method has been characterized as one of the most appropriate due to its fast and exponential convergence.

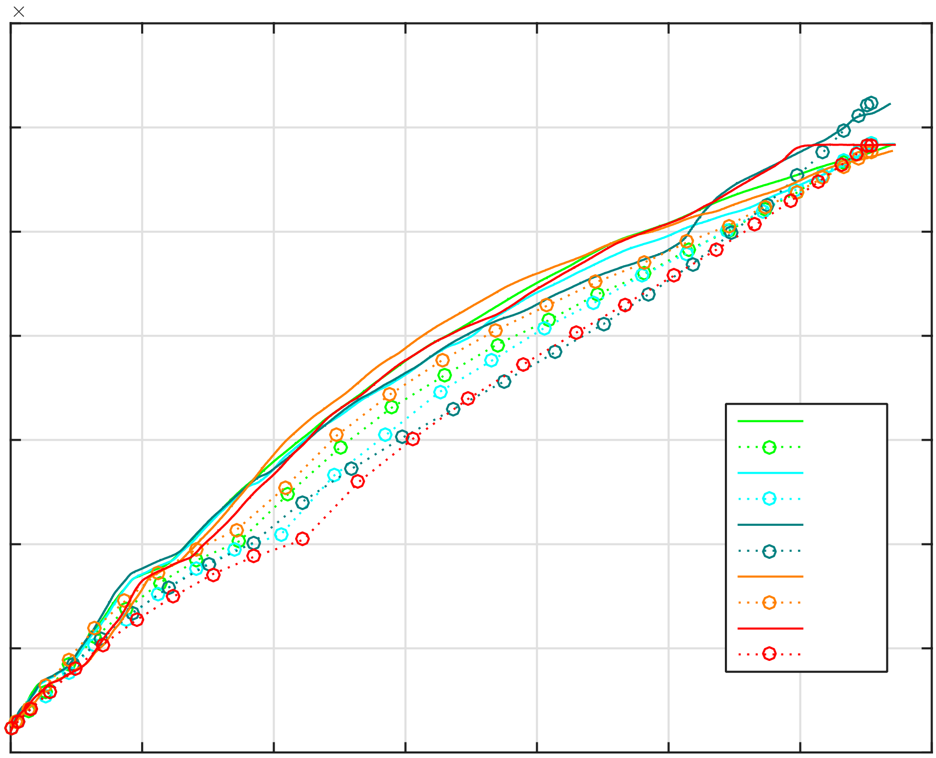

Figure 21: Vertical profile comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios, as a function of distance

The simulated profiles on the diagrams, fig.21 and fig.22, specify the optimal CCOs according to the mentioned factors respecting the principles of this operating technique. Besides, the curves exhibit the evolution of the altitude versus distance and time for the optimization of the CCO vertical profile. As it is shown in the diagram, the simulated trajectories represent more stable profiles and better balanced compared to real trajectories, as a consequence of the continuous operations effects. Additionally, the diagram presents a noticeable transition on the profile due to the effect of the operational speed limitation. It is worth mentioning that the calculated trajectories require longer times.

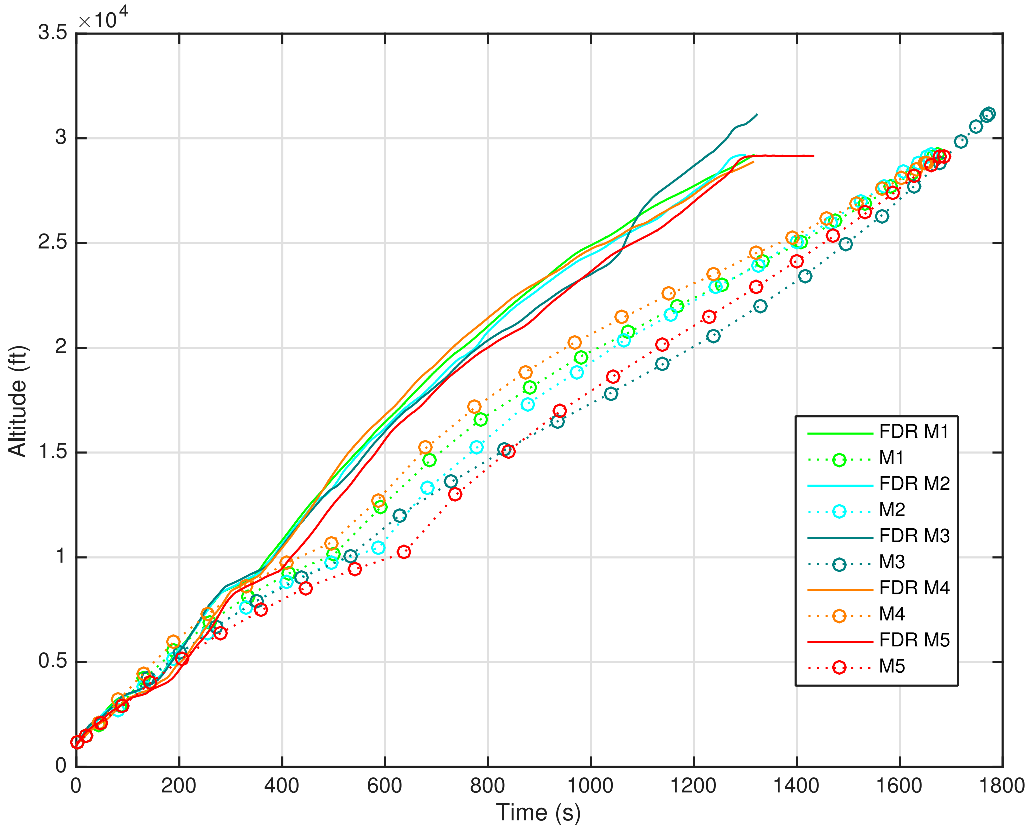


Figure 22: Vertical profile comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios, as a function of time

Figures; 23 and 24 present the variation of the GWs during the continuous climbs. The considered values correspond to a representative set of operational configurations from the real sample data. It is possible to distinguish a modest variation of their values along the path when performing a continuous climb. This is a characteristic of optimization processes, which tend to be out from significant and instantaneous variations. Within diagrams 23 and 24, it can be appreciated that the conventional departures present bigger variations at early stages, mainly related to more aggressive departure profiles as well as existence of level-off segments. Contrariwise, the lines corresponding to conventional departures and the optimized CCOs become closer at later stages that is due to the fact that the departure profiles for conventional flights become more efficient and thereby, presenting smaller variations on GWs.

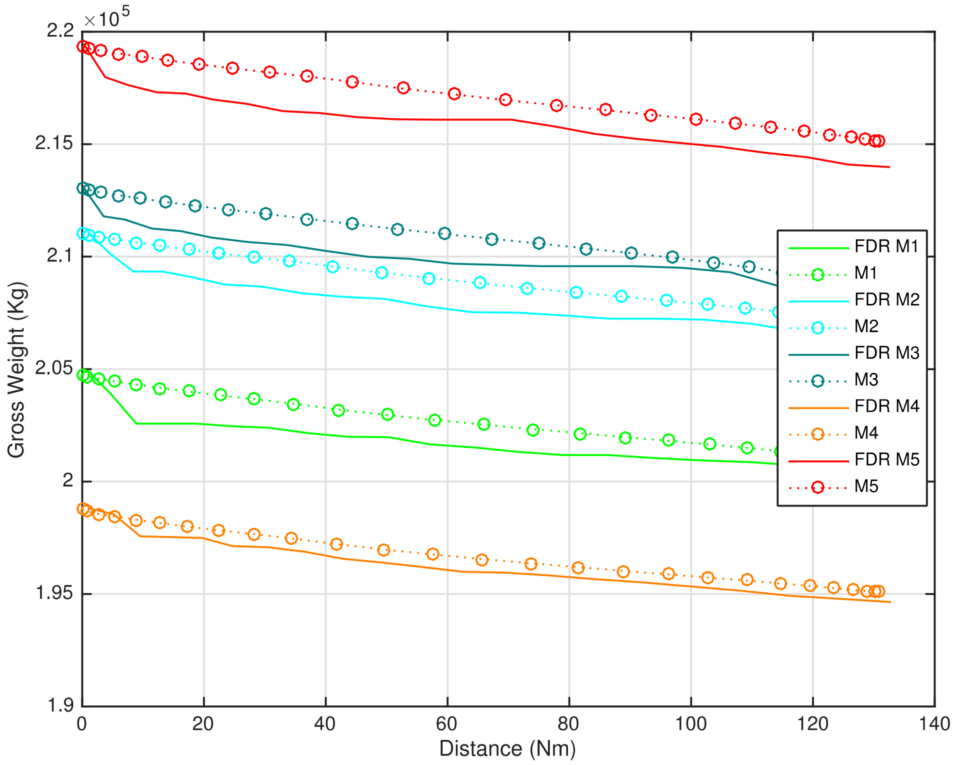


Figure 23:Gross Weights comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of Distance.

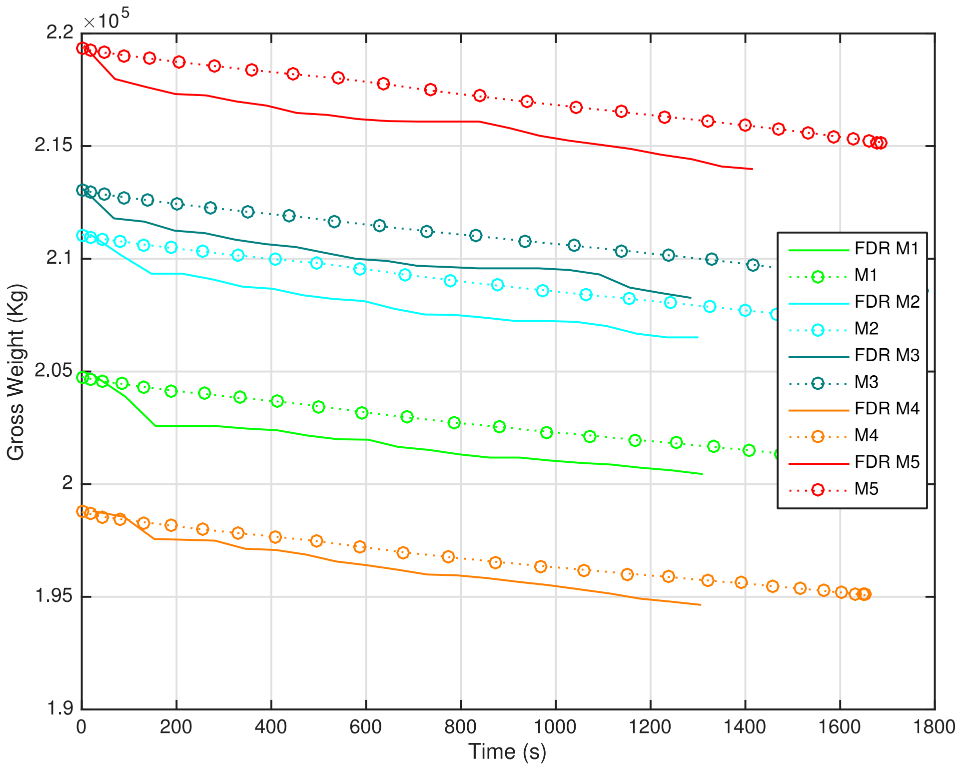


Figure 24: Gross Weights comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of Time.

When considering the fuel consumption, the optimized departures do not present significant variations along the flight procedure. These behaviors are shown on the following figures; 25 and 26. At earliest stages, the numerical model may present higher consumption levels, albeit the main trend is that real departures quickly reach and exceed significantly the optimized departures. This effect is due to aggressive Rate Of Climbs (ROC) and unplanned accelerations observed at low altitudes. The effects of level-offs become evident when compared to continuous climb profiles, particularly before resuming the climb at the end of the level-off segments where it is required an increase on thrust. This situation is hardly aggravated on low altitudes and therefore, at early stages the lines corresponding to conventional departures present steeper profiles. The existence of leveled segments is associated to multiple ATC clearances. The operational benefit of the facilitation of this operating technique is the reduced number of ATC clearances and therefore the controllers' workloads. As manifested on these figures 25 and 26, the unplanned departure or the interruption of the CCO due to intermediate clearance causes unnecessary variations on thrust. These are translated on higher fuel consumption and noise effects in the vicinity of the airports.

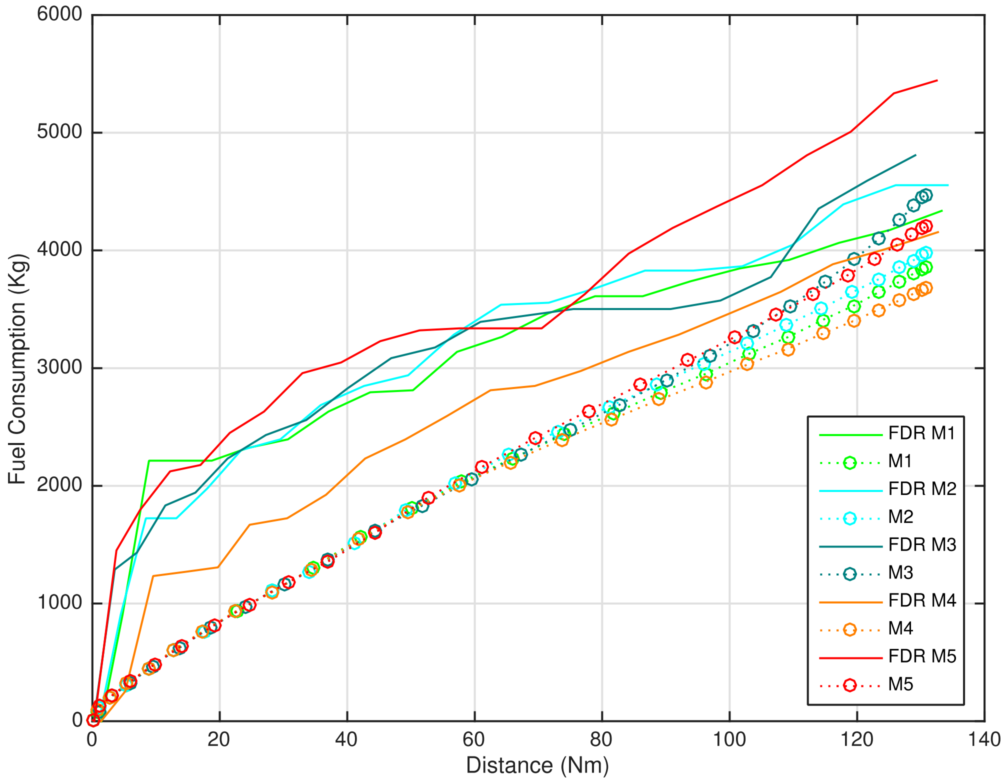


Figure 25: Fuel Consumption comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of distance.

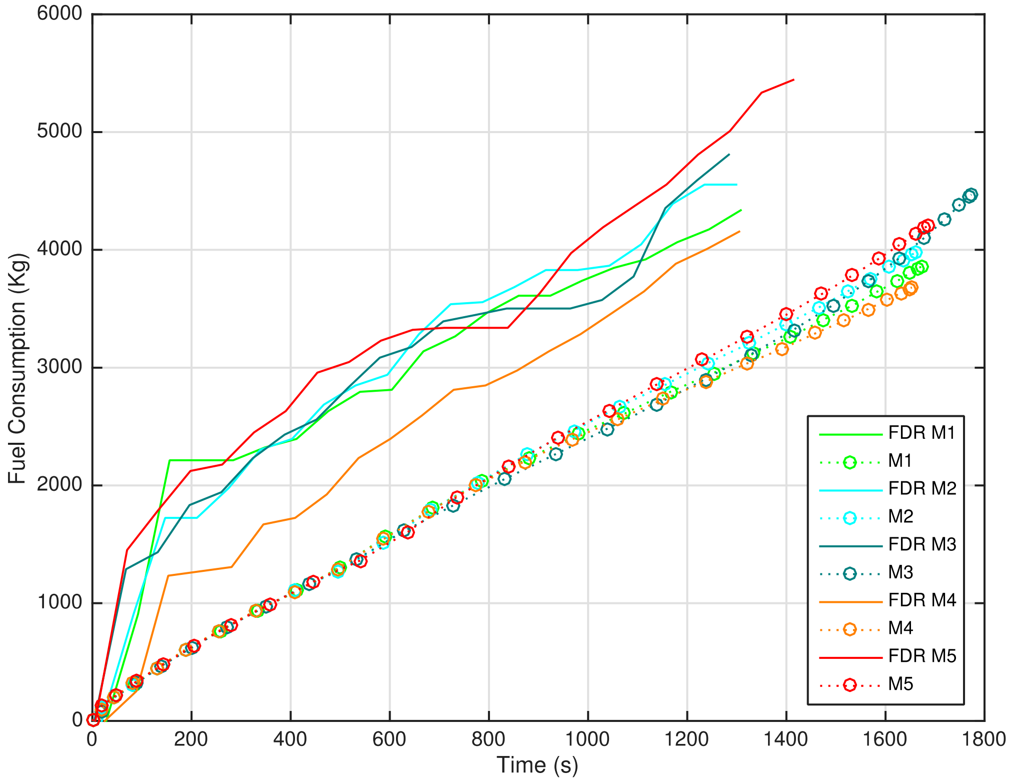


Figure 26: Fuel Consumption comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of time.

ICAO heavy category aircraft are more sensible to inefficient operational procedures, especially when configured for long-range flights. Likewise, this also seems to be the case with higher Gross Weights for the same aircraft type. Therefore, the higher the Take-Off Weight, the bigger exposition to inefficiency of departure vertical trajectories will be. The comparison between these long range departures against domestic flights manifests the fact that the latter present more aggressive profiles. However, it is interesting to note the comparison for the fuel consumption of the optimized departure aircraft against the real one for similar Maximum Take-Off Weight. In the particular case of the study in this chapter, the values present encouraging benefits as shown on table 4. The achieved fuel savings are between 7% and 23% when comparing similar aircraft configurations. It becomes evident the potential savings that this technique could offer when compared to aggressive real departures or instantaneous and ineffective variations on thrust engine settings.

Table 4: Fuel Savings

| Aircraft | M1 | M2 | M3 | M4 | M5 |
|---|---|---|---|---|---|
| Fuel Savings (%) | 11.06 | 12.79 | 7.07 | 11.41 | 22.87 |

As indicated on the documents, [14] & [47], there is an operational constraint in terms of maximum airspeed below 10.000ft. Furthermore, this restriction of 250Kt airspeed has been manifested through the analysis of the FDR data, which becomes evident on the representations 27 and 28. For this work, the relationship between True Air Speed (TAS) and Indicated Air Speed (IAS) has been considered as a function of the air density (i.e. the altitude) and the air temperature.

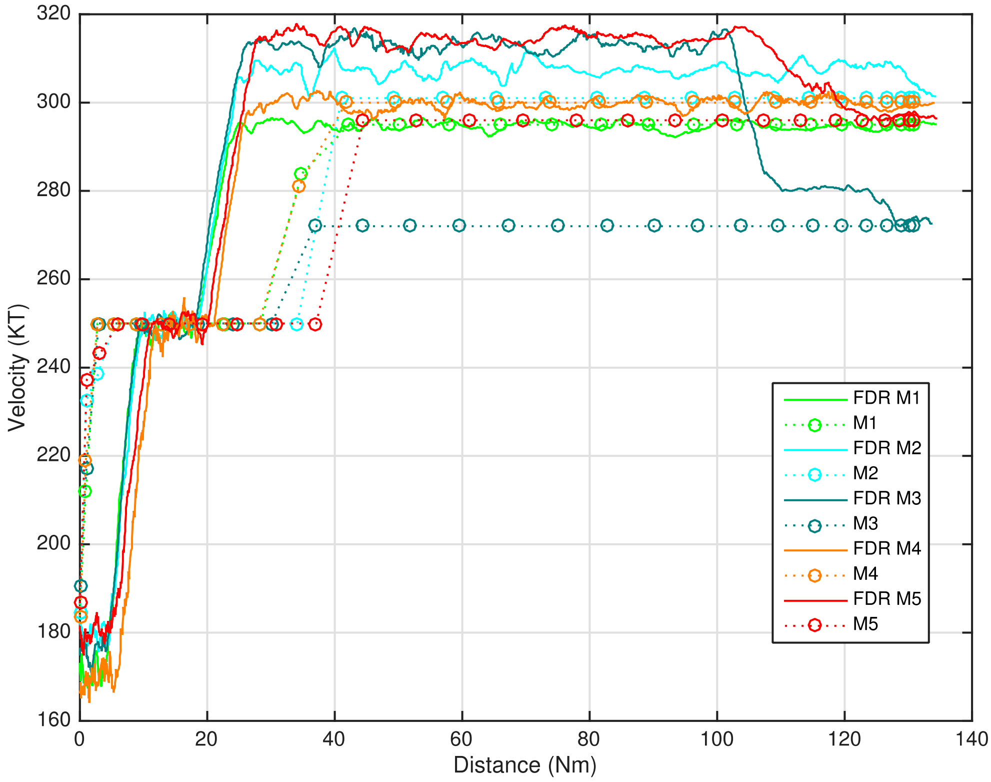


Figure 27: Velocity comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of distance.

The requirement of this speed constraint is a relevant issue in terms of flight efficiency. Without challenging the compliance of this operational constraint and based on results obtained in parallel to the achieved results for this investigation, it is important to note that this operational restriction does not seem to be beneficial economically and environmentally speaking. If this operational constraint could be removed, there may be a potential enhancement of efficiency as confirmed by Mitchell et al. on [39].

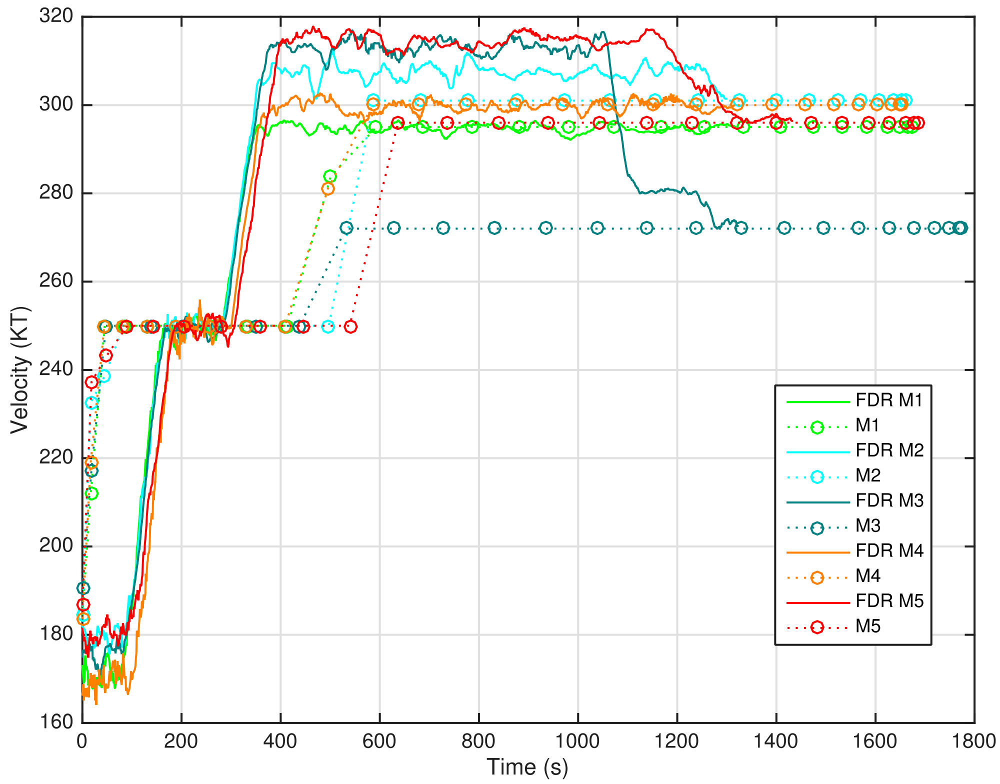


Figure 28: Velocity comparison between conventional (real) and CCO (optimized) flight data for several mass scenarios as a function of time.

Moreover it is possible to identify that at the beginning of the climb phase, the simulated aircraft tend to perform earlier acceleration than real ones. Once the FL 100 has been attained, which is where the operational constraint in term of speed is released, the acceleration is carefully managed against the rate of climb in order not to trigger excessive fuel consumption. In addition, the velocity tend to be lower when the initial GW is higher, which bears out its dependence on fuel consumption.

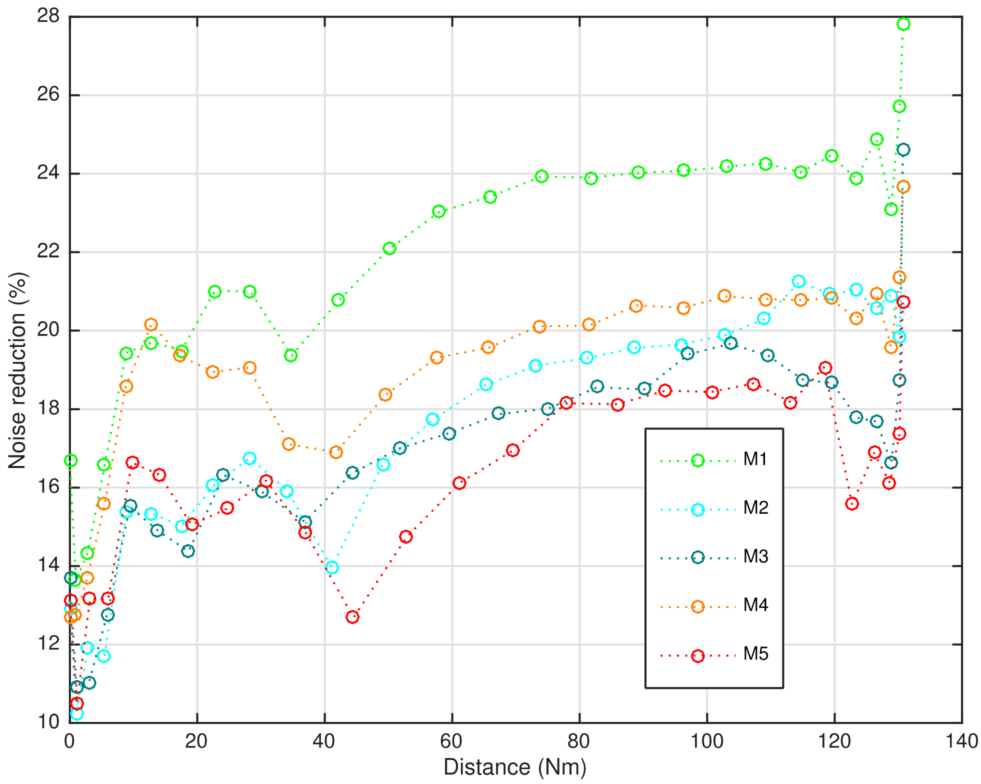


Figure 29:Noise reduction when comparing CCO (optimized) against conventional (real) flight data for several mass scenarios, as a function of Distance (%)

Additionally, the representation fig.29 has been presented for the sake of clarity and completeness in terms of noise impacts. It represents the noise reduction versus distance. The noise savings achieved along the trajectory goes between 10% and 28% when comparing the real flights against the optimized departures. The diagram present minor savings at early stages and at those points where attaining 10.000ft. According to the latter it becomes evident again, now in terms of noise, the inefficiency of the aforementioned ATC constraint. These results bear out the significant benefits of this optimization, which in noise effects realm improves the noise impacts in the vicinity of airports.

## 5.5 Conclusion

This work presents the results achieved while performing a multi-objective optimization of a departure trajectory based on continuous operating techniques. It has been possible to perform the combination of operational characteristics of a CCO procedure with the application of a widely used mathematical method. It is aimed at optimizing departures in terms of specific environmental factors being able to respect ATC operational constraints as well as specific boundary conditions.

The benefits are illustrated through 10% - 28% of noise reduction and through 7% - 23% of fuel burn savings. These results manifest the environmental advantages to the communities in the vicinity of the airports and the efficiency in fuel consumptions, therefore transmitting evidences that highlight the importance of the continuous operations for the aviation community. Thereby, the departure optimization achieved, in terms of noise and fuel emissions respecting the continuous climbs operations philosophy in combination with a Chebyshev-Gauss-Lobatto (CGL) Pseudospectral Method, reinforces the idea of transmitting the importance of CCOs and furthermore, promotes the usage of this operating technique in TMA. However, it is worth mentioning the fact that the applicability to any current TMA needs to be pitched at the right level, taking into account the local operational preferences as well as the prioritization of the considered optimization factors.

From an operational point of view it is interesting to note that the reduction in level-off segments allows the application of optimal thrust settings and the optimal air speed when attaining the target altitude. In this regard, the reduction in tactical interventions may impact positively in controllers' workload.

Nevertheless, despite the fact of the benefits presented in this work, the encouragement of the application of the CCO requires the operational integration in busy environments. At last but not at least, it is important to remark the operational issue regarding the compliance with the vertical profile, which need to be tackled.

# 6 Analyzing the Departure Runway Capacity Effects of Integrating Optimized Continuous Climb Operations

Performing Continuous Climb Operation (CCO) procedures enable the reduction of the environmental footprint and the improvement of the trajectory efficiency when individually operated as concluded in the previous chapter. However, its operation may affect negatively the overall operational efficiency at Terminal Maneuvering Areas (TMAs). The estimation of capacity is a matter of paramount importance to all airports planning and analyzing the capacity effects of this particular operational technique on a certain scenario will definitely help on evaluating its potential applicability. In this paper, departure runway capacity at the Adolfo Suárez Madrid-Barajas airport was operationally evaluated when introducing CCOs. The considered trajectories consisted of multi-objective optimized CCOs based on the optimal control theory, using the pseudospectral direct numerical method. These scenarios allowed addressing of the incremental variations of CCOs versus conventional departures, through fast time simulation, with the objective to assess the effects on the operations.

## 6.1 Introduction

Defined as an uninterrupted climb flight operation allowing the aircraft to attain initial cruise flight level at an optimum air speed with optimal thrust settings [6], the Continuous Climb Operation (CCO) leads to a significant fuel economy and environmental benefits. The improvement of flight trajectories through the execution of a flight profile optimized to the performance of an aircraft represents a significant enabler for Trajectory-Based Operations (TBO), which is one of the four pillars (four-phase improvement), defined on Single European Sky ATM Research (SESAR)[3].

At a local level, continuous operating techniques, such as CCOs, can significantly reduce the environmental footprint in living areas around the airports. Besides, this technique allows the airspace users to plan and, ideally, to fly a trajectory which will be closer to their preferences whilst complying with operational constraints. This may be translated into positive contributions on cost benefits through satisfying the airspace users' business needs.

As previously indicated in previous chapters, the successful application of a CCO should not be simplistically reduced to the operation of an uninterrupted climb procedure, which implies inexistent level-off segments. It is important to note the importance of factors like the aircraft, airport type, aircraft weight, runway, Standard Instrument Departure (SID), and operational constraints when identifying the CCO profile optimized to the performance of the aircraft.

However, the integration of a CCO-operating technique in a Terminal Maneuvering Area (TMA) requires the analysis of one of the most important parameters on airport planning, which is capacity. This Key Performance Area (KPA), which is one of the eleven KPAs defined by ICAO [2], at high-density terminal areas motivated the interesting work presented by Li et al. [48]. The model introduced for terminal area design is mainly focused on arrival trajectories. It is important to highlight that the integration of a pure CCO has not been directly considered by recent investigations; therefore, an assessment of the operational limitations and its potential effects would be tempting.

In Europe, SESAR [3] targets up to 30% reduction in departure delays. On the other hand, its environmental expectation targets up to 10% reduction in $CO_2$ emissions including a positive impact on noise and air quality. Along with this KPA, the operational efficiency aims up to 6%

reduction in flight time and up to 10% reduction in fuel burn. The successful achievement of all these targets is not trivial considering that the implementation of an environmental friendly operational procedure may produce negative effects on other KPAs.

It is likely to obtain local positive environmental effects through the application of optimized CCOs whilst affecting negatively airport efficiency operations. In other words, a new operating technique that seems to be beneficial when it is applied in isolation may not be quite beneficial when integrated as a part of a complete scenario. The study presented within this chapter is aimed at studying the capacity effects when applying optimized CCOs. The Adolfo Suárez Madrid-Barajas airport (ICAO code, LEMD) has been selected as the test scenario to evaluate the effects on capacity when facilitating CCOs. The study has been enabled by a consolidated multi-objective software model, which was previously developed by the authors, for the computation of aircraft trajectories when performing optimal CCOs in terms of noise and fuel consumption.

## 6.2 Departures at Adolfo Suárez Madrid-Barajas

Adolfo Suárez Madrid-Barajas is the largest airport in Spain with 378,566 total operations in 2017. Considered as one of the largest airport in Europe by physical size, it is the country's busiest airport in Spain, and Europe's sixth busiest. The airport is predominantly operated in north configuration and runway (RWY) 36L was selected as the preferred option for this study. In particular, the chosen flight segments go from ground to waypoint (WPT) AVILA. A shorter flight segment, which is common for two Standard Instrument Departures (SIDs): Bardi Two Tango (BARDI2T) and Cáceres One Tango (CCS1T), and a longer flight segment, which is shared by Bardi Two Kilo (BARDI2K) SID and Cáceres One Kilo (CCS1K) SID. The operations of these SIDs are limited by the performance of the aircraft and aircraft type as clarified below.

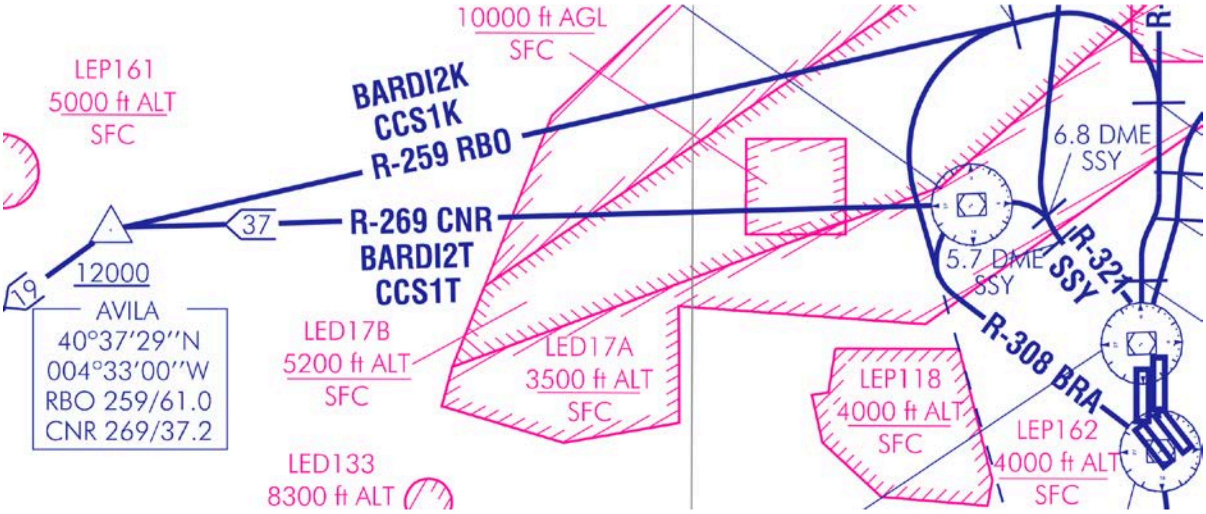


Figure 30: SIDs RWY 36L. Detailed view of selected flight segments associated to BARDI2T/CCS1T & BARDI2K/CCS1K SIDs.

Fig. 30 shows a zoom view of the published chart, which includes the SIDs for RWY 36L, usable at daytime. SIDs BARDI2T/CCS1T are only allowed to authorized aircraft and, thus, BARDI2K/CCS1K becomes mandatory to listed aircraft due to noise restrictions. Published noise abatement procedures are applicable to all takeoffs, unless exceptionally cancelled due to an event that cannot be reasonably anticipated.

This is a challenging scenario as the performance of the aircraft plays a relevant role when performing BARDI2K/CCS1K or BARDI2T/CCS1T SID. The facilitation of CCO when performing these departure segments must satisfy the airspace restrictions and operational constraints.

## 6.3 Aircraft Performance

This section should gather the aircraft dynamics equations considered for this study. In order to avoid duplication and considering that the set of differential equations of the aircraft were formulated within section 3.6.9 of chapter 3 of this document, the reader is kindly referred to the aforementioned section for further details.

## 6.4 Operational constraints and boundary conditions

The studied scenario corresponds to RWY 36L at the Adolfo Suárez Madrid-Barajas airport. The surveillance data has been analyzed in order to identify the operational constraints of the scenario prior to the performance of the simulations. Flows for departures and arrivals have been studied. Moreover, it has also been analyzed the potential interaction of the inbound &

outbound flows against the modeled flight segment for SIDs BARDI2T/CCS1T and BARDI2K/CCS1K.

Determining the capacity effects when facilitating CCOs has been applied to the aforesaid SIDs, where the performance of the aircraft plays a significant role. The clearance for flying a CCO technique does not take the aircraft operator away from being compliant with the numerous operational constraints.

The considered flight segments start with a climb on the runway heading directly to DVOR/DME SSY and finish when crossing AVILA waypoint at 12000ft or above. The operation of these flight segments may be influenced by aircraft performance limitations, which may be translated on negative effects depending on the selected SID. It is worth mentioning that assuming the initial Air Traffic Control (ATC) clearance of maintaining 13000ft and requesting flight level change e - route may not stop a continuous climb operation in the first instance.

The assumed separation for departures is time based. The considered value is 120 seconds between any combinations of aircraft types. Regarding the operational constraints, Table 5 gathers the operational constraints, like Minimum Climb Gradient (MCG) and Knots Indicated Airspeed (IAS), among others.

Table 5: Operational Constraints.

| SID | BARDI2T/CCS1T | BARDI2K/CCS1K |
|---|---|---|
| MCG | 6.4% to 10000 ft | 7.5% to 4500 ft |
| KIAS constraints (1) | 5.7 DME SSY: 180-240 kt | 15 DME BRA h ≥ 6500ft |
| KIAS constraints (2) | h ≤ 10000ft KIAS ≤ 250 kt | |
| AVILA (2) | h ≥ 12000ft | |

The computational cost for finding the solution is significantly higher when the problem is applied to actual scenarios due to the mandatory compliance of actual operational constraints. The initial conditions on the studied procedure are taken at the moment the aircraft lines up for taking off. Table 2 summarizes the main boundary conditions considered when modeling the departures for the considered aircraft types, Airbus 319 (A319) and Airbus 330 (A330). The surveillance data analysis performed through additional hand-tailored MATLAB models enabled the operational assessment of departure and arrival flows as well as the calculation of some relevant parameters indicated within table 5. The analysis of the surveillance data brings up interesting facts, for example, SID BARDI2T/CCS1T is highly operated by mediums compared to heavies. Considering this, it is not realistic to consider a medium aircraft operating BAR-DI2K/CCS1K SID.

## 6.5 Model

Traditionally, tactical controllers manage the aircraft within their airspace domain and provide clearances to specific altitudes based on the characteristics of the traffic in terms of complexity and airspace layout. A conventional departure trajectory, which has been vertically limited, presents several levels-off before reaching the cruise level. There is a limit to the number of aircraft a controller can keep track of at one time, so as airspace has to be subdivided in airspace sectors, the flights require leveled segments. These leveled segments on the vertical profile penalize the aircraft efficiency and prevent the aircraft from flying its ideal trajectory. Conversely, the performance of an optimized CCO that allows the aircraft to attain initial cruise flight level at an optimum air speed with optimal thrust settings brings noteworthy benefits to the flight efficiency. Chapter 2 of this dissertation illustrates a standard departure and an optimized CCO where the differences between the departure flight paths can be appreciated.

The mathematical method used for the optimization of the CCO is based on the optimal control theory, which aims at determining the control input that will cause a system to achieve the control objectives, whilst satisfying the constraints and also optimizing some performance criterion. The trajectory optimization problem was solved following an open loop terminal control problem that allows the constraints acting on the dynamical system to be considered in a way that the obtained trajectory will be admissible.

Commercial aircraft trajectory problems have been tack-led through open loop optimal control techniques as referenced and introduced within chapter 3 of this dissertation. However, optimal control problems are characterized for being highly nonlinear, and thus, it becomes certainly difficult to find analytical solutions. Numerical methods are typically used for this purpose, and direct methods fit the approach for the trajectory optimization problem.

### 6.5.1 Optimal Control Problem

In order to avoid duplication and considering that the OCP was formulated within section 3.2 of chapter 3 of this document, the reader is kindly referred to the aforementioned section for further details.

In the investigation presented within this chapter, the operational flight paths were obtained through multi-objective optimization process based on CCO principles by a CGL pseudospectral method. The calculations were executed through a hand-tailored software tool implemented on AMPL modeling language [35] for Airbus A319 and A330 aircraft, using IPOPT as the NLP solver. The latest Base of Aircraft Data (BADA 4.1 [36]) supported the AMPL self-implemented optimization model. AMPL is an algebraic modeling system for mathematical programming of large-scale optimization problems. For the sake of clarity, a solver is defined as the number-crunching algorithm that computes optimal solutions. The calculated optimal trajectories were stored in a database for further processing.

### 6.5.2 Optimization Criteria

The environmental optimization criterion has been modeled considering two magnitudes: maximum A-weighted sound level ($\mathrm{L_{max}}$) and fuel burn. Aiming at supporting this multiobjective optimization, the weighted combination of the aforementioned factors has been implemented as follows:

$$J = a.Noise + b.Fuel\ consumption \tag{57}$$

where a and b are adjustable weighting constants. The values of these constants are directly related to the trade-off between noise exposure and fuel consumption/emissions. In this study, both factors have received the same weighting avoiding the prioritization of one of them. It is out of the scope of this chapter to present the analysis of Pareto for the aforesaid weighting constants. The considered parameter for noise optimization, maximum A-weighted sound level $\mathrm{L_{max}}$, is based on the methodology employed by the Integrated Noise Model (INM [41]). The core of this methodology relies on the Noise-Power- Distance (NPD).

### 6.5.3 Departure Capacity Model

The following steps were required to establish the appropriate enablers that allow addressing of the main objective of this study, in other words, the means of evaluating the operational implications of integrating optimal CCOs.

The scenario was modeled considering operational and physical constraints. The derivation of the runway utilization rates when performing CCOs required the construction of a departure capacity model. It was flexibly constructed, based on the MATLAB software tool, in a number of stages:

1. The physical constraints were analyzed for variability across departure routes
2. The different operational constraints were compared to determine which were the most dominant
3. Preprocess of surveillance data and FDR data to generate database
4. Databases (actual data) were processed through an additional MATLAB model to determine arrival and departure traffic flows, as well as aircraft type patterns
5. In parallel, the optimal CCOs were simulated whilst being complied with the identified constraints
6. The databases (optimized trajectories) were compiled by using the data obtained from the simulations
7. The databases were processed by the capacity model with the aim of determining the runway utilization rates

The departure capacity model processed data regarding the considered aircraft types (A330\A319), whilst ensuring no loss of separation. The separation values for this calculation were 1000ft (vertical) and 3NM (horizontal) [14]. The table below presents the evaluated aircraft types per SID.

Table 6: Aircraft types and their associated mass (M) per SID for optimal CCOs and conventional departures

| SID | BARDI2T/CCS1T | BARDI2K/CCS1K |
|---|---|---|
| Aircraft (CCO) | M1/M2/M3 (A319) / M1/M2/M3 (A330) | M1/M2/M3 (A330) |
| Aircraft (conventional) | M1/M2/M3 (A319) /M1/M2/M3/M4 (A330) | M1/M2 (A330) |

As it is possible to appreciate on it, the A319 were not considered for BARDI2K/CCS1K taking into account the findings from the surveillance data analysis. It bears out the fact that mediums operating the long leg when departing west are not usual. Regarding the aircraft mass for CCOs, several highly representative take-off mass values were considered where M1 represents the lightest of the studied actual data sample. The figures are not provided in purpose.

Different path lengths, speeds, altitudes, ATC constraints, performance limitations, and operational-cleared levels are some of the numerous parameters, which were considered. The construction of the model was reviewed and discussed with operational staff ensuring the most realistic scenario. The selected mechanism of evaluating the capacity is based on the Monte Carlo simulations that were hand-tailored through MATLAB.

## 6.6 Results

Estimating capacity is a matter of paramount importance to all airports planning and analyzing the capacity effects of this particular operational technique on a certain scenario helped on evaluating its potential applicability. The selected method to evaluate CCOs was to study them against actual conventional departures. From an operational point of view, it has been assumed departure separation is based on time. In this regard, a standard time separation of 120 seconds between consecutive departures has been considered. Unfortunately, the combination of certain conventional departures and optimal CCOs may require longer time spacing while ensuring safety operations between the aircrafts along the SIDs.

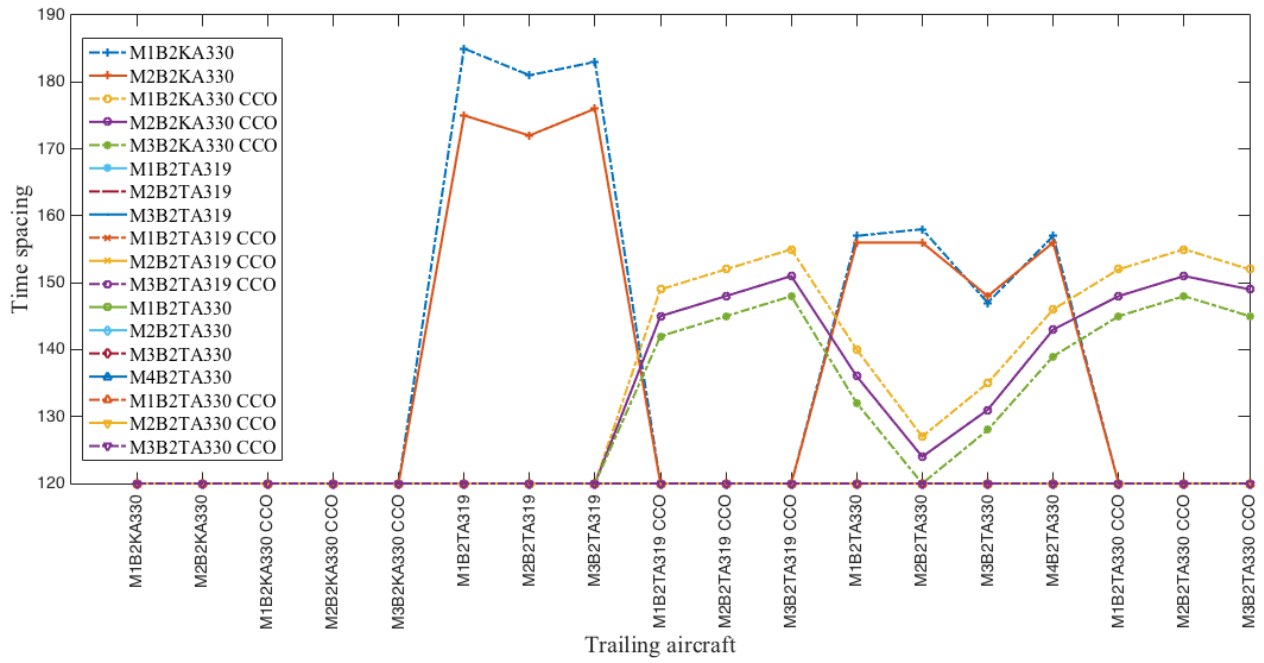


Figure 31: Time separations between aircraft operating BARDI2T/ CCS1T & BARDI2K/CCS1K SIDs.

Fig. 31 gathers the information regarding the effects on time spacing in view of the results obtained, is influenced, by the SID and the combination of leading (each represented line) and trailing aircraft (abscissa axis). The following points address those combinations of departures where longer time spacings, than the standard 120 seconds, are required to ensure no loss of separation.

1. M1B2KA330 (.-+). Being the leading aircraft, an A330 departing BARDI2K/CCS1K whilst performing a conventional departure, it is necessary for an increase of time spacing between 61 and 65 seconds when the trailing aircraft is A319 and between 28 and 38 seconds for A330 performing conventional departures through BARDI2T/CCS1T
2. M2B2KA330 (-+). Leading aircraft, an A330 departing BARDI2K/CCS1K whilst performing a conventional departure, it is necessary for an increase of time spacing between 52 and 56 seconds when the trailing aircraft is A319 and between 27 and 36 seconds for A330 performing conventional departures through BARDI2T/CCS1T
3. M1B2KA330 CCO (.-o). Being the leading aircraft, the lightest A330 (M1) departing BARDI2K/CCS1K whilst performing a CCO, it is necessary for an increase of time spacing between 29 and 35 seconds when the trailing aircraft is A319 performing CCOs through

BARDI2T/CCS1T and between 7 and 35 seconds for A330 departing through BARDI2T/CCS1T

4. M2B2KA330 CCO (-o). Being the leading aircraft, the A330 (M2) departing BARDI2K/CCS1K whilst performing a CCO, it is necessary for an increase of time spacing between 25 and 31 seconds when the trailing aircraft is A319 performing CCOs through BARDI2T/CCS1T and between 4 and 31 seconds for A330 departing through BARDI2T/CCS1T
5. M3B2KA330 CCO (-o). Being the leading aircraft, the heaviest A330 (M3) departing BARDI2K/CCS1K whilst performing a CCO, it is necessary for an increase of time spacing between 22 and 28 seconds when the trailing aircraft is A319 performing CCOs through BARDI2T/CCS1T and up to 28 seconds for A330 departing through BARDI2T/CCS1T

Considering the above factors it is interesting to highlight two findings: first of all, when the leading aircraft is performing a conventional departure via the long leg of the SIDs (BARDI2K/CCS1K), the standard time spacing requires to be increased. This time spacing is likely to be higher when the trailing aircraft type is lighter than the leading one. Secondly, it is interesting to note the fact that when the leading heavy aircraft is performing a CCO via BARDI2K/CCS1K, it is necessary for more time spacing for the trailing aircraft flying CCOs than conventional departures.

### 6.6.1 Runway Capacity Effects Due to CCO Expedition.

Finally, the effects on capacity for each combination of leading-trailing aircraft were calculated using Monte Carlo simulations. The Monte Carlo simulations were conducted using a hand-tailored model based on MATLAB software tool. Its main objective was to obtain the capacity values per hour of operation considering the previously calculated time spacing between different combinations of aircraft. The simulations were conducted for 10.000 hours per scenario. The model addresses 11 scenarios depending on the percentage of CCOs that covers a total of 110.000 hours analyzed:

(1) Scenario 1.100% CCOs

(2) Scenario 2. 90% CCOs/10% conventional departures

(3) Scenario 3. 80% CCOs/20% conventional departures

(4) Scenario 4. 70% CCOs/30% conventional departures

(5) Scenario 5. 60% CCOs/40% conventional departures

(6) Scenario 6. 50% CCOs/50% conventional departures

(7) Scenario 7. 40% CCOs/60% conventional departures

(8) Scenario 8. 30% CCOs/70% conventional departures

(9) Scenario 9. 20% CCOs/80% conventional departures

(10) Scenario 10. 10% CCOs/90% conventional departures

(11) Scenario 11. 100% conventional departures

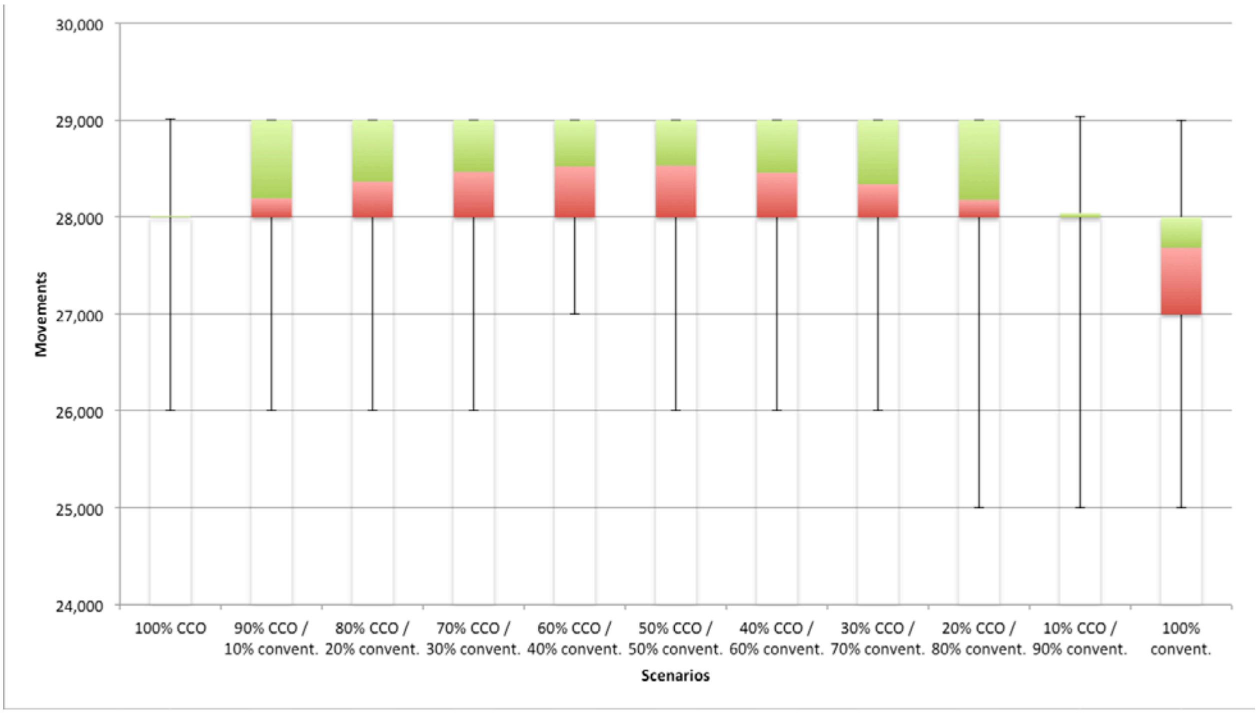


Figure 32: Capacity: Maximum number of aircraft that can be accommodated per hour according to aforementioned scenarios.

Figure 32 gathers the information regarding the boxplot for each scenario. It allows the reader to appreciate the key results and to identify the key characteristics. The median, which is represented by the line in the box, represents a measure of the center of the data, and the interquartile range box (the green and the red box) brings the distance between the first and the third quartile. Besides, the interquartile range box brings the distance between the first and the third quartile. Last but not the least, the whiskers show the ranges for the bottom 25% and the top 25% of the data values.

1) Scenario 1. The median capacity is 28 movements per hour, and the capacity is as low as 26 and as high as 29. The capacity values are less variable than other scenarios
2) Scenario 2. The median capacity is 28.2 movements. Most of the capacity values are between 28 and 29, and the boxplot manifests top-skewed data, which means that most of the capacity values are lower. The capacity values are as low as 26 and as high as 29
3) Scenario 3. Median capacity value is 28.4, and the interquartile range box is the same as the previous scenario. The boxplot represents top-skewed data. The whisker values are as low as 26 and as high as 29
4) Scenario 4. The median capacity value is 28.5, and the interquartile range box and the whiskers have the same values on the previous scenario. In this case the main difference is regarding the skewed data, which seems to be slightly top-skewed
5) Scenario 5. The median capacity is 28.5, the interquartile range box remains as before but the bottom whisker increases up to 27. In this case, the data is not skewed
6) Scenario 6. The median capacity is 28.5. The interquartile range box is the same as before, but in this case, the lower whisker goes back to 26. The data distribution is symmetric
7) Scenario 7. Median value is 28.5. Similar to scenario 6 where it is possible to appreciate a change of trend regarding the data, which is slightly top-skewed
8) Scenario 8. Median value is 28.3. The main difference compared to scenario 6 is that in this case, it is clearly top-skewed data
9) Scenario 9. Median value is 28.2. In this case, the lower whisker decreases down to 25, and the scenario is clearly top-skewed data
10) Scenario 10. Median capacity value is 28 movements per hour, and the capacity is as low as 25 and as high as 29. The capacity values are less variable than other scenarios

11) Scenario 11. Median capacity value is the lowest, 27.7. The capacity is as low as 25 and as high as 29. Most of the capacity values are between 27 and 28, and the boxplot manifests bottom-skewed data, which means that most of capacity values are higher

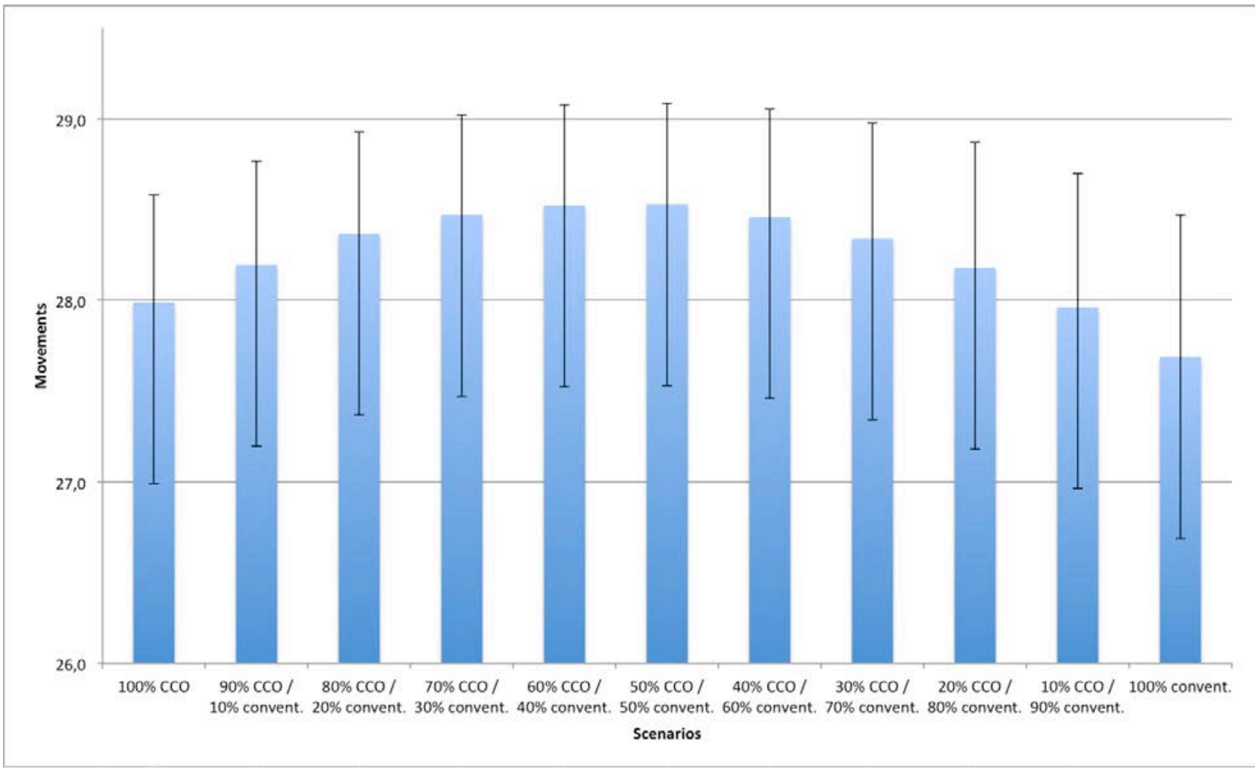


Figure 33: Capacity: Mean capacity values are represented by the bar plot and the associated standard deviations of the sample are illustrated by the whiskers.

Fig. 33 reveals that the median values for the studied scenarios vary between 27.7 and 28.5. It is interesting to note the fact that those scenarios where the percentages of each type of traffic are similar, the median presents its highest values. The standard deviation appreciated for the scenarios with lower percentage of CCOs are higher. This indicates that the values are more dispersed.

## 6.7 Conclusions

In view of the obtained results, the integration of traffic performing CCOs on departures does not affect negatively in terms of runway capacity. Therefore, it may be argued that whilst the combination between leading-trailing aircraft on mixed departures may affect the capacity, the effect is within an acceptable limit.

The integration of CCO does not necessarily require a specific ATM tool at the controller's working position but the procedures should support them. Nevertheless, the results suggest that integrating CCOs along with a combination of a departure sequence tool tend to mitigate the characteristics of these operating techniques.

Unlike standard arrival routes where aircrafts are tactically guided by air traffic controllers, SID routes tend to follow fixed flight paths. Thus, the optimization of the vertical profile may be considered an appropriate initiative for departure efficiency.

Allowing the airspace user to fly optimized continuous climb operations will bring significant benefits in greenhouse gas and noise emissions in the vicinity of airports. From the operational point of view, it will lead to more consistent flight paths whilst reducing the number of required radio transmissions. As a consequence, this may be traduced on lower pilot and air traffic controller workload.

This study reinforces the idea of transmitting the importance of CCOs and, furthermore, promotes the usage of this operating technique in TMAs.

# 7 Optimized Continuous Climb Operations as part of Airport Collaborative Decision Making

The International ATM research programs around the world are putting in place significant effort on obtaining innovative solutions for the modernization of ATM. However, these catalogues of ATM solutions are usually focused on individual implementation of them. As a consequence, there are conundrums that remain unresolved from an operational point of view when applying simultaneously more than one of these innovative solutions, at the same scenario. In this work, considering that the previous chapter concluded that CCOs in isolation does not affect negatively Capacity, it is envisaged to perform an assessment of the implications when applying two of the most relevant ATM priorities that aims at enhancing the efficiency, predictability, and cost effectiveness of the operations at and in the vicinity of airports. In particular, the considered innovative solutions for this analysis are Airport-Collaborative Decision Making (ACDM) and CCO. The work proposed an optimal control model for minimizing the delay of a departure mix of aircraft, considering the performance of optimal CCOs using pseudospectral direct numerical method. Despite the extensive research available within the literature on aircraft sequencing, to the best knowledge of the authors, is not common to find a detailed consideration of TMA operations. Instead of dealing with pure runway-sequencing, this work dealt with departure sequencing aspects, tackling the problem with the consideration of conventional flight segments and optimal departure vertical trajectories.

## 7.1 Introduction

A long queue of aircraft lined up and ready for departure may be beneficial for maximizing runway efficiency; however, it is not beneficial for reducing environmental footprint due to inefficient fuel consumption, noise and greenhouse gas emissions.

As part of the Aviation System Block Upgrades (ASBU) systems engineering modernization strategy, Global Air Navigation Plan (GANP) [2], the International Civil Aviation Organization (ICAO) gives priority to a number of initiatives. Along these lines, global air navigation initiatives for future Air Traffic Management as previously referenced, are putting significant efforts on innovative researches for efficient flight path and airports operations performance improvements areas, among others.

The growing global traffic demand of air transportation is translated into an increased number of aircraft movements. This would likely take place in the coming years due to a shift paradigm on ATM trends through a transition between a Hub ATM operational model and a point-to-point ATM operational model, where smaller and more efficient aircraft will become more predominant. However, considering the undoubtedly increase of the operations during the coming years, it is of paramount importance the enhancement of the overall operational efficiency.

As part of these initiatives, different solutions that refer to improved operational procedures and ATM technologies have been prioritized in Europe, particularly at Terminal Maneuvering Areas (TMAs) and airports. Regarding the latter, as major airports around the world are very limited in terms of creating new infrastructure, it is highly appreciated to put in place optimization methods for its better use. Notwithstanding, the implementations of these solutions are rarely studied from a combined point of view.

The study presented in this chapter aims at assessing simultaneously two ATM solutions whose target performance benefits are Airport Operations and Efficient Flight Paths, as per ASBU modules convergence approach within GANP [2]. Explicitly, the considered innovative solutions are focused on Airport-Collaborative Decision Making (ACDM) and Continuous Climb Operations (CCO) module capabilities respectively. The latter mainly focused on improved flexibility and efficiency in departure profiles and the former essentially focused at enhancing the overall efficiency of airport operations, in particular in this work, focused on departure sequencing.

Regarding Efficient flight paths target performance benefit, CCO is defined as an uninterrupted climb flight operation allowing the aircraft to attain initial cruise flight level at optimum air speed with optimal thrust settings [6], leading to significant fuel economy and environmental benefits as previously introduced.

In terms of Airport Operations target performance benefit, A-CDM is defined within ICAO Manual doc. 9971 [49] as follows; “Airport collaborative decision making (ACDM) is an operating model which includes a set of processes that allows aerodromes, aircraft operators, air traffic controllers, ground handling agents and pilots to exchange operational information and work together to efficiently manage operations at aerodromes”. The decision making process needs to be facilitated through the share of accurate and timely information along with the adoption of new procedures, mechanisms and tools. Eurocontrol A-CDM Implementation manual [10] defines a series of concept elements for the successful implementation of A-CDM at any airport. The most relevant one is Departure Sequencing concept element that refers to optimizing the pushback sequence through automated sequencing and thus, replacing the “First-Come-First-Served (FCFS)” principle with “Best-Planned-Best-Served” (BPBS).

Eurocontrol A-CDM implementation manual [10] defines pre-departure sequencing as the order that aircraft are planned to depart from their stands (push off-blocks orders), taking into account partners’ preferences. As a consequence, this will allow air traffic controllers to handle the Target of Block Times (TOBTs) obtained from the turn-round process in a way that flights can depart from their stand in a more efficient and optimal order. As a result, the BPBS principle will be translated into a pre-departure sequence and afterwards, into a runway sequence.

## 7.2 Scheduling Optimization

Air traffic controllers responsible for ground movements at the visual control room have the objective of providing an expeditious flow of traffic to the runway. These are time consuming tasks that require big effort at planning and tactical phases considering aircraft parking positions, taxi routes, heterogeneous mix of aircraft, airfield traffic situation and tactical adjustments due to time or procedural restrictions among others. Considering these, departure sequencing, being manually performed by controllers, is quite challenging, very demanding and far from optimal, typically as the case of big and complex airports.

Optimizing scheduling of operations in a runway is a problem that has been extensively tackled, frequently not concentrated on departures. The works from Ball et al. [50] as well as Allahverdi et al. [51] presented a suite of approaches for departure scheduling resolution based on different objectives functions and constraints. Focusing mainly in the literature regarding the departure phase, it is possible to appreciate a big variety of cases pivoting around cost functions based on environmental impact, runway throughput, airline benefits, airborne delay, etc. It is worth mentioning the works from Atkin et al. [52][53][54], that aimed at increasing the runway throughput and reducing the runway delays as well as exploring further factors like weight of delays, taxi times and take-off times re-negotiations. Moreover, a relevant work dealing with ground delays is the research from Kotynek and Richeta [55], focused on delaying aircraft before departing at origin to reduce congestion at destination. However, more considerations like safety, ATC workloads, airline operating costs for more sophisticated definitions of delay are modeled within the studies from Kuhn KD [56] and Manley B. & Sherry L. [57].

Most of the literature available is focused on airport efficiency, tackling the departure sequence optimization with quite simplified modeling of TMAs. Despite the recent work from Samà et al. [58] that could be considered as a remarkable enhancement on modeling sequencing problem within TMAs, was concluded the need for integrating the scheduling project with en-route aspects and additional objectives, airborne constraints and variables. Thereby, this work aims at completing the works already presented in terms of departure sequencing that will allow the reader to gain further insights on introducing optimized CCO trajectories as part of the sequence optimization model.

Continuous operating techniques, such as CCOs, can significantly reduce the environmental footprint in living areas around the airports. Besides, this technique allows the airspace users to plan and ideally, to fly a trajectory which will be closer to their preferences whilst complying with operational constraints. In parallel, from a collaborative point of view, the provision of an optimized and robust departure sequence reduces waiting times at holding points, runway delays and enhances predictability. It is important to note that the departure sequence allows the A-CDM stakeholders (with special mention of airlines) to share their preferences for the order at departing phase. Considering this, combining efficiency of airport operations and departure profiles will not only contribute positively to the environmental footprint at airports and TMAs but also provide airspace users to play a more active and influencing role on the operations. This is not a negligible aspect, as the active interaction of stakeholders on operational decision-making will be an enabler of the future of ATM in alignment with flight and flow information in a collaborative environment (FF-ICE) [59].

The literature gathers a wide variety of algorithms that have been developed to solve the optimal flight-sequencing problem. These algorithms fall under three main categories, which are: dynamic programming, evolutionary or heuristic algorithms and tree-based search algorithms. In case further details are required, S. Chandrasekar and I. Hwang [60] presented on his work an interesting analysis of them. For the study within this paper, it was decided to perform the application of optimal control model to the departure sequence problem. This mathematical method used for the optimization aims at determining the control input that will cause a system to achieve the control objectives, whilst satisfying the constraints and also optimizing some performance criterion. Additionally, the considered trajectories consisted on a series of conventional departures along with multi-objective optimized CCOs based on optimal control theory, using pseudospectral direct numerical method.

## 7.3 Departures at Adolfo Suárez Madrid-Barajas

Adolfo-Suárez Madrid Barajas is the largest airport in Spain with 409,832 total operations in 2018. Considered as one of the largest airport in Europe by physical size, it is the country's busiest airport in Spain, and Europe's sixth busiest. The airport is predominantly operated in North configuration and runway (RWY) 36L was selected as the preferred option for this study.

In particular, the chosen flight segments go from ground to waypoint (WPT) AVILA. A shorter flight segment, which is common for two Standard Instrument Departures (SIDs): Bardi Two Tango (BARDI2T) and Cáceres One Tango (CCS1T), and a longer flight segment, which is shared by Bardi Two Kilo (BARDI2K) SID and Cáceres One Kilo (CCS1K) SID. The operations of these SIDs are limited by the performance of the aircraft and aircraft type as clarified below.

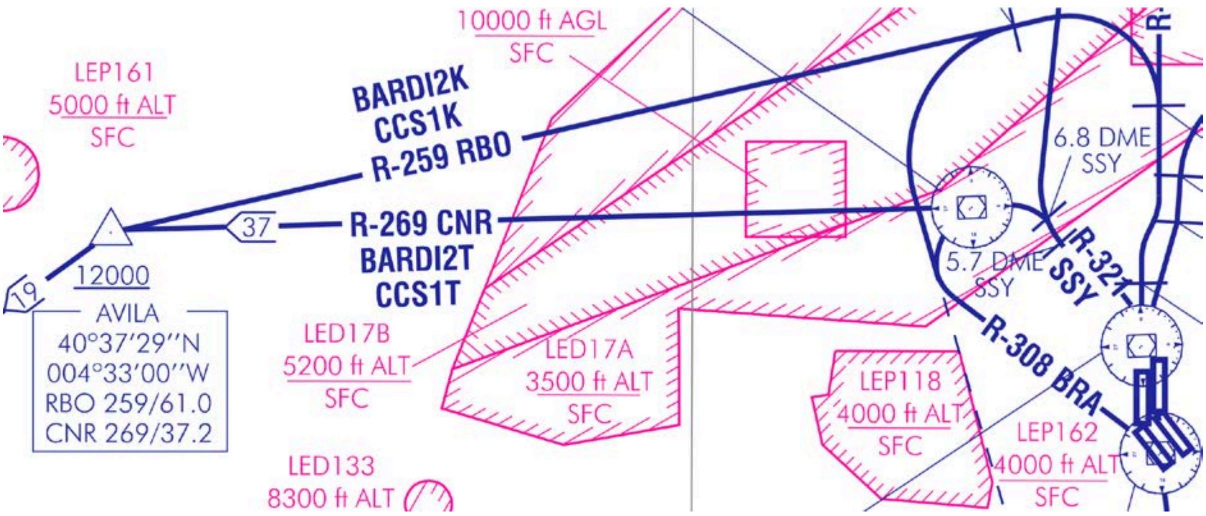


Figure 34: Detailed view of SID RWY 36L: Usable during day time.

Figure 34 shows a zoom view of the published chart, which includes the SIDs for RWY 36L, usable at daytime. SIDs BARDI2T/CCS1T are only allowed to authorized aircraft and, thus, BARDI2K/CCS1K becomes mandatory to listed aircraft due to noise restrictions. Published noise abatement procedures are applicable to all takeoffs, unless exceptionally cancelled due to an event that cannot be reasonably anticipated. This is a challenging scenario as the performance of the aircraft plays a relevant role when performing BARDI2K/CCS1K or BARDI2T/CCS1T SID. The facilitation of CCO when performing these departure segments must satisfy the airspace restrictions and operational constraints.

## 7.4 Aircraft performance

This section should gather the aircraft dynamics equations considered for this study. In order to avoid duplication and considering that the set of differential equations of the aircraft were formulated within section 3.6.9 of chapter 3 of this document, the reader is kindly referred to the aforementioned section for further details.

### 7.4.1 Problem description

The International ATM research programs around the world are putting in place significant effort on obtaining innovative solutions for the modernization of ATM. However, these catalogues of ATM solutions are focused on normally focused on individual implementation of them. As a consequence, there are conundrums that remain unresolved from an operational point of view when applying simultaneously more than one of these innovative solutions, at the same scenario. Therefore, in this work, it is envisaged to perform an assessment of the implications when applying two of the most relevant ATM priorities that aims at enhancing the efficiency, predictability, and cost effectiveness of the operations at and in the vicinity of airports.

The optimal sequencing of departure operations on a runway ensures the most convenient usage of the runway during a period of time. In other words, optimization of runway sequence aims at minimizing the “makespan”, known as the time required for performing a set of operations at the runway. This would allow the controllers to safely manage higher number of movements whilst improving take-off time predictability and reducing waiting time at runway holding points.

With this work we proposed an optimal control model for minimizing the makespan of a departure mix of aircraft, considering the performance of optimal CCOs using pseudospectral direct numerical method.

### 7.4.2 Runway sequence optimization model

Sequence Optimization is one of the main key elements of A-CDM concept. Eurocontrol A-CDM implementation manual [10] defines Pre-departure sequencing Concept Element as the order that aircraft are planned to depart from their stands (push off-blocks) taking into account partners' preferences. The optimal sequencing allows ATC to handle the target times that aircraft will be ready for push-back, obtained from the turn-round process in a way that flights can depart from their stands in a more efficient and optimal order. Thus, ATC, taking due account of the operational situation, will be able to consider this calculated optimal order that will be cleared for departing in the most efficient and predictable manner.

Despite the extensive research available within the literature on aircraft sequencing, to the best knowledge of the authors, is not common to find a detailed consideration of TMA operations. Instead of dealing with a pure runway-sequencing project, this work dealt with a wider concept that tackles departure sequencing problem with the consideration of conventional flight segments and optimal departure vertical trajectories. The following parameters must be considered in order to calculate the optimal sequence; the target time each aircraft will be ready for Take-off (known as TTOT), the assigned standard instrument departures, the separation between aircraft, flow constraints, the parking stands, the queue length, the minimum departure intervals, operational capacity, assigned runway and the arrival flow.

Providing an expeditious flow of traffic to the runway requires the consideration of planning and tactical aspects of the operation. Our work is mainly focused on planning phase, and it is out of the scope the study of tactical aspects regarding the airfield situations. Considering the right level of automation, i.e. routing functions currently available within some of the main ATM solutions in the market, more efficient and predictable variable taxi times can certainly be provided which, will allow ATC to translate the departure sequence at the runway into a start-up sequence. An optimal departure sequence is highly appreciated by airport handling agents, airport operators and airlines that can effectively plan their operations in advance. Regarding our study, this is translated into the fact that the parameters regarding taxi-times, parking stands as well as the corresponding routes for taxiing-out will have default values.

The studied scenario corresponds to RWY 36L at Adolfo-Suárez Madrid Barajas airport. The runway was considered as an independent runway for departures only for this problem. Yet it may seem to be a simplistic scenario, the arrival flow at the aforesaid airport in north configuration is handled by RWY 32L and 32R and it is not considered for departure runway sequence but considered regarding the departure and arrival flows within the TMA. The surveillance data was analyzed in order to identify the operational constraints of the scenario prior the performance of the simulations. Regarding the departure flows, the optimization model created for this study is able to consider potential dependencies between RWY 36L and 36R. This could have been implemented within the model considering a single departure sequence for both runways applying the separation constraints according to the operational model.

The scenario was modeled considering operational and physical constraints. It was flexibly constructed, based on AMPL software tool, in a number of stages:

1) The physical constraints were analyzed for variability across departure routes
2) The different operational constraints were compared to determine which were the most dominant
3) Pre-process of surveillance data and FDR data to generate database
4) Departure schedule extracted
5) Databases (actual data) were processed through an additional matlab model to determine arrival and departure traffic flows, as well as aircraft type patterns
6) In parallel, departure flight trajectories were extracted from the database, an also the optimal CCOs were simulated whilst being complying with the identified constraints
7) The databases (optimized trajectories) were compiled by using the data obtained from the simulations
8) The databases were processed by the runway sequence optimization model with the aim of determining the optimal departure sequences

Flows for departures and arrivals have been studied. Moreover, it has also been analyzed the potential interaction of the inbound & outbound flows against the modeled flight segment for the considered SIDs. The optimized CCOs are studied on SIDs BARDI2T/CCS1T and BARDI2K/CCS1K.

The departing traffic, where the aircraft that has been cleared for departure take off the runway and initiate the climb following the SID route, is subject to separation constraints. The assumed separation for departures is time based. The considered value is 120 seconds between any combinations of aircraft types as extracted from the analysis of the surveillance data. A wake turbulence separation minimum has the aim of preventing the hazards associated to wake vortex encounter. However, when separation minima are more conservative than wake turbulence separation minima is not necessary that ATC apply any special measure in this regard. Nevertheless, ICAO's existing wake vortex separation rules that are based on three (3) aircraft categories (Heavy-H, Medium-M and Light-L) were defined nearly 4 decades ago. Recent investigations, as per the initiative driven by Eurocontrol [61] through European Wake Vortex Re-Categorization (RECAT-EU) project has demonstrated a much more precise categorization of aircraft that improves safety and offers opportunity for increasing capacity. Considering a default departure time separation of 120 seconds between any aircraft, means that the aircraft type will not affect the sequence. Despite our model is able to consider the new categorization, the comparison between both wake vortex separations categories is out of the scope of this study.

### 7.4.3 Model

The model is sketched as is shown in fig. 35. Note that the problem is represented as a directed graph based on a set of nodes, which are representing the entrance into an area, and a set of directed arcs interconnecting the nodes,

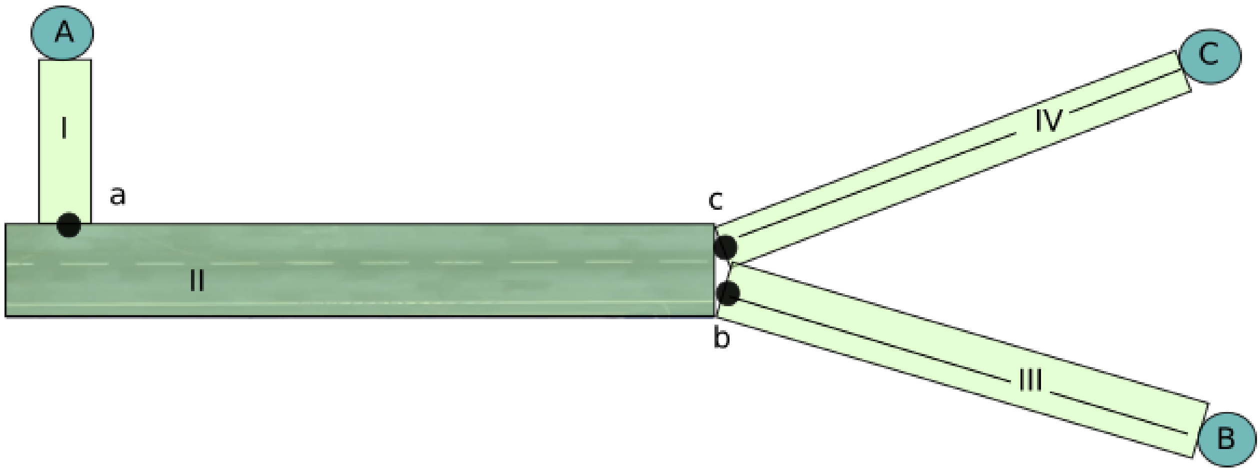


Figure 35: Model schema

The model is based on;

1. four (4) different areas (I, II,. III, IV),
2. three (3) nodes denoting transitions between areas (a,b,c),
3. 1 initial node (A),
4. and two (2) final departure nodes (B &C) - final node "B" makes reference to the end of the considered departure procedure for SID BARDI2T; meanwhile C is the corresponding to SID BARDI2K.

The capacity allowed for the area I is three (3) aircraft at the same time reference thus, allowing that number of aircraft at the holding points. This allowed us to model the operational aspect of having enough buffer that allows Air Traffic Control not to lose any slots, whilst maintaining the runway throughput. The capacity at other areas (II, III & IV) is considered as one (1) aircraft. Besides, the capacity in the different nodes (A, a, b, B, c, C) is one (1) aircraft at the same time. The flight scheduled departure time from node A is planned to be 100 seconds separated from one flight to the following one. Additionally, the scheduled arrival time at node B or C is composed by the following times; time from A to a is considered 10 seconds, time estimated for the runway movement (from a to b or c) is 20 seconds and the time from b or c to B or C is the one that is presented on table 7. Note this table has been computed based on previous studies. Finally, the maximum ground holding delay is set up at one hundred (100) seconds.

Table 7: Departure duration (seconds) depending on Standard Instrument Departure, Aircraft and Type of departure.

| SID | BARDI2T (short) | | | | BARDI2K (long) | | | |
|---|---|---|---|---|---|---|---|---|
| Aircraft type | A319 | | A330 | | A319 | | A330 | |
| Type of departure | Convent. | CCO | Convent. | CCO | Convent. | CCO | Convent. | CCO |
| Time (seconds) | 510 | 585 | 585 | 593 | N/A | N/A | 665 | 689 |

The sequence optimization model considers the full departure trajectories including conventional and optimal CCOs, whilst ensuring no loss of separation. The conventional departure trajectory profiles were extracted from the built database. As it is possible to appreciate on the table, the A319 were not considered for BARDI2K/CCS1K taking into account the findings from the surveillance data analysis. It bears out the fact that mediums operating the long leg when departing west are not usual.

### 7.4.4 Optimization criteria

The selected optimization criterion is the minimum delay, which has been modeled considering variable $\mathrm{w}_{\mathrm{n,t}}^{\mathrm{f}}$ defined in $\mathrm{f} \in \mathcal{F}, \mathrm{n} \in \mathcal{N}_{\mathrm{f}}, \mathrm{t} \in \mathcal{T}$. This decision variable is a binary matrix being true if the flight f arrives at time t at node n, false otherwise. Thus, the optimization criterion has been modeled as follows,

$$J = min \sum_{f \in \mathcal{F}} \left( \sum_{\substack{t \in \mathcal{T}_{fn} \\ o \in O_f}} (cg_f) \cdot (w_{o,t}^f - w_{o,t-1}^f)(t - d_f) \right) \tag{58}$$

where $\mathrm{cg}_{\mathrm{f}}$ is an adjustable weighting constant that represents the associated cost for ground delays for flight $\mathrm{f} \in \mathcal{F}$.. The value of this constant is directly related to the fuel consumption/emissions amongst others. In this study, the factor has a default weighting value of “1”. It is out of the scope of this chapter to present the analysis of Pareto for the aforesaid weighting constant.

## 7.5 Results

The delay at the departure runway sequence has a significant impact on the departure sequence optimization as per the impact it has on the operations. It is defined as the difference between the target times for take-off and the scheduled planned for take-off.

The scenarios studied are as follows;

1) 50% convent. 50% CCO A319 BARDI2T
2) 50% convent. A319 50% convent. A330 BARDI2T
3) 50% convent. A319 50% CCO A330 BARDI2T
4) 50% convent. A319 BARDI2T 50% convent. A330 BARDI2K
5) 50% convent. A319 BARDI2T 50% CCO A330 BARDI2K
6) 50% CCO A319 50% convent. A330 BARDI2T
7) 50% CCO A319 50% CCO A330 BARDI2T
8) 50% CCO A319 BARDI2T 50% convent. A330 BARDI2K
9) 50% CCO A319 BARDI2T 50% CCO A330 BARDI2K
10) 50% convent. 50% CCO A330 BARDI2T
11) 50% convent. A330 BARDI2T 50% convent. A330 BARDI2K
12) 50% convent. A330 BARDI2T 50% CCO A330 BARDI2K
13) 50% CCO A330 BARDI2T 50% convent. A330 BARDI2K
14) 50% CCO A330 BARDI2T 50% CCO A330 BARDI2K
15) 50% convent. 50% CCO A330 BARDI2K
16) 100% convent. A319 BARDI2T
17) 100% CCO A319 BARDI2T
18) 100% convent. A330 BARDI2T
19) 100% CCO A330 BARDI2T
20) 100% convent. A330 BARDI2K
21) 100% CCO A330 BARDI2K

The results obtained are as per the following figure where the blue color corresponds to scenarios with only conventional departures, green color is for pure optimal CCOs and the mix of green and blue is for the different mix of type of departures. As it can be observed within the diagram, it is interesting to highlight two main findings; the minimum delay can be achieved by a scenario comprising only pure optimal CCOs. Conversely, it can be appreciated that the maximum delay could take place with only a mix of conventional departures.

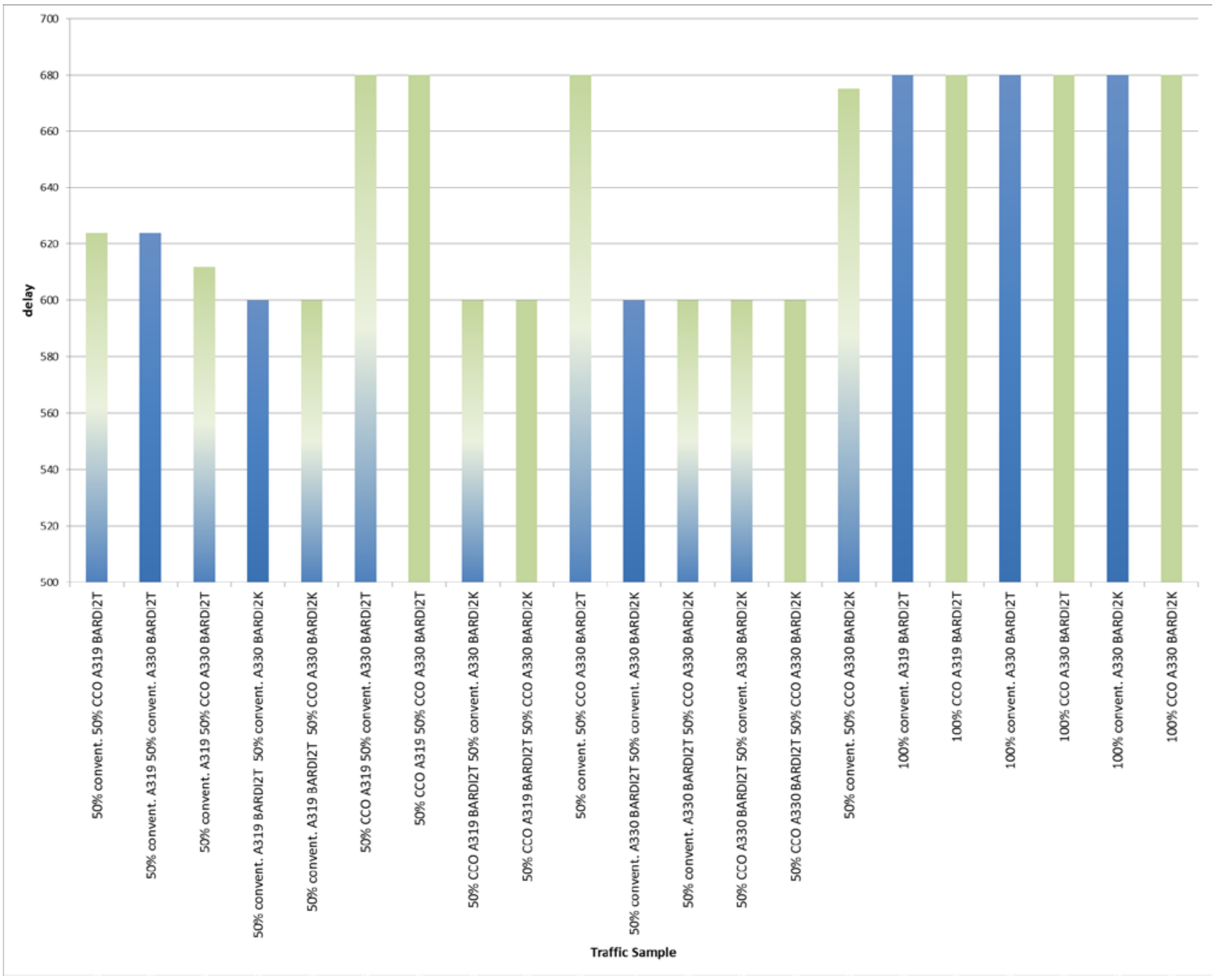


Figure 36: Departure delays according to the considered scenarios

## 7.6 Conclusions

In view of the results, the integration of traffic performing optimal CCOs as part of an optimal departure scheduling does not present negative effects in terms of delays. Therefore, it may be argued that whilst the integration of optimal CCOs, with longer flying times for the same departure leg, the effects on delays are due to other factors.

The integration of CCO does not necessarily require a specific ATM tool at the controller's working position. However, an advanced departure management during planning phases that allows ATC to cover SID flying times depending on the departure types, may be considered as an appropriate initiative for the enhancement of airport and TMA efficiency.

Allowing the airspace user to fly optimized continuous climb operations as well as to play a more active and influencing role on the operations through their preferences will bring efficiency of airport operations and departure profiles. As a consequence, this will not only be traduced on efficiency of operations but also making airspace users more active on airspace operations.

This study reinforces the idea of transmitting the importance of CCOs and, furthermore, promotes the usage of this operating technique as part of A-CDM.

# 8 Conclusions of this dissertation

The growing global traffic demand of air transportation, translated into an increased number of aircraft movements would likely take place in the coming years due to a shift paradigm on ATM trends through a transition between a Hub ATM operational model and a point-to-point ATM operational model, where smaller and more efficient aircraft will become more predominant.

The departure phase of flight has also been identified as a key area where substantial environmental benefits could be achieved.

After deep analysis of real radar and real Flight Data Recorder (FDR), it has been identified the existence of certain indicators (for example: level-off segments and aggressive vertical profiles) that manifest the fact that flown departure trajectories are usually far from optimal. As a consequence, negative effects in the vicinity of the airports become a serious concern. This challenge drove the investigation on setting up the right climb strategy, particularly optimized Continuous Climb Operations (CCOs), which enables the aircraft to attain cruise flight levels at optimum configuration and thus improving the efficiency in terminal airspaces, while contributing to the enhancement of the environment.

In order to face it, this investigation tackled this problem thanks to the combination of hand-tailored model through AMPL modelling language based on Pseudospectral methods, supported by Base of Aircraft Data (BADA 4.1) and calibrated with real data. The FDR data also gave us the capability to crunch and analyze the simulation results against real operational data. It has not only been applied to multiple environmental factors but also has been restricted by real ATC operational constraints.

In an effort to contribute for sustainable transport, particularly Aviation, this work thereby presents the environmental benefits through the multi-objective trajectory optimization of flight departures by means of Chebyshev-Gauss-Lobatto (CGL) at terminal airspace operation. Aligned with global aviation initiatives, it also contributes to the promotion and strengthens of Continuous Climb Operations (CCO). The results bear out the efficiency and expeditious character of this continuous operating technique and its potential contribution to the sustainable air transportation.


Figure 37: Image representing different departure aircraft at earlier stages of their climb procedure. *Alisdair Miller Photography*

Despite CCO has yet to be implemented by many Air Navigation Service Providers (ANSPs), it allows airspace users to plan and ideally, to fly user-preferred optimal flight paths which, represent a significant enabler towards Trajectory Based Operations (TBO). However, CCO operation may affect negatively to the overall operational efficiency of a particular airport. The estimation of capacity is a matter of paramount importance to all airports planning and analyzing the capacity effects of this particular operational technique on certain scenario will definitely help on evaluating its potential applicability.

This bears out the challenge that lies ahead regarding the implementation of CCOs. In order to face it, this investigation tackled this problem considering multi-objective optimized CCOs based on optimal control theory, using pseudospectral direct numerical method. Moreover, the derivation of the runway utilization rates when performing CCOs required the construction of a departure runway capacity model. It was flexibly constructed, based on Matlab software tool, in a number of stages. Initially, covering the effects of combinations of leading-follower aircraft on departure time spacing and finally, allowing the operational assessment of the capacity effects.

The results concluded that the integration of traffic performing CCOs on departures does not affect negatively in terms of runway capacity. Therefore, it may be argued that whilst the combination between leading-trailing aircraft on mixed departures may affect the capacity, the effect is within an acceptable limit. The integration of CCO does not necessarily require a specific ATM tool at the controller's working position but the procedures should support them. Nevertheless, the results suggest that integrating CCOs along with a combination of a departure sequence tool tend to mitigate the characteristics of these operating techniques.

An ATM priority like Airport-Collaborative Decision Making (ACDM) promoted by International ATM research programs that aim at enhancing the efficiency, predictability, and cost effectiveness of the operations at and in the vicinity of airports may be negatively affected. In fact, the evaluation exercises of combined ATM solutions will help on addressing the conundrums that remain unresolved from an operational point of view.

In order to tackle it, this investigation face this challenge considering multi-objective optimized CCOs based on optimal control theory, using pseudospectral direct numerical method along with conventional departures within a particular TMA environment. Moreover, the analysis of the departure delays on the runway scheduling problem when integrating CCOs required the construction of a departure management model. It was flexibly constructed, based on AMPL software tool, in a number of stages.

The conclusion was that the integration of traffic performing optimal CCOs as part of an optimal departure scheduling does not present negative effects in terms of delays. In addition to this, it is important to highlight that allowing the airspace user to fly optimized continuous climb operations and to play a more active and influencing role on the operations through their preferences will bring efficiency of airport operations and departure profiles. As a consequence, this will not only be traduced on efficiency of operations but also making airspace users more active on airspace operations.

Thereby, it can be concluded that TMA can be enhanced through the integration of CCO. However, it is worth mentioning the fact that the applicability to any current TMA needs to be pitched at the right level, taking into account the local operational preferences as well as the prioritization of the considered optimization factors.

# 9 List of Publications

The list of publications resulting from this PhD. work is given in inverse chronological order as follows:

**Journal Papers**

M. Villegas Díaz, V. F. Gómez Comendador, J. García-Heras Carretero, R. M. Arnaldo Valdés, Environmental benefits in terms of fuel efficiency and noise when introducing continuous climb operations as part of terminal airspace operation, International Journal of Sustainable Transportation (2019) 1–11doi:10.1080/15568318.2019.1651924. URL https://doi.org/10.1080/15568318.2019.1651924

M. Villegas Díaz, F. Gómez Comendador, J. García-Heras Carretero, R. M. Arnaldo Valdés, Analyzing the departure runway capacity effects of integrating optimized continuous climb operations, International Journal of Aerospace Engineering 2019 (2019) 10. URL https://doi.org/10.1155/2019/3729480

V. F. Gómez Comendador, R. M. Arnaldo Valdés, M. Villegas Díaz, E. Puntero Parla, D. Zheng, Bayesian network modelling of atc complexity metrics for future sesar demand and capacity balance solutions, Entropy 21 (4). doi:10.3390/e21040379. URL https://www.mdpi.com/1099-4300/21/4/379

**Conferences**

M. Villegas Díaz, F. Gómez Comendador, J. García-Heras Carretero, R. M. Arnaldo Valdés, Enhancing operational efficiency of terminal maneuvering areas through continuous climb operations, in: EUCASS (Ed.), 8th European Conference for Aeronautics and Space Sciences (EUCASS), 2019. URL http://www.eucass2019.eu/detailed-programme/

Peter Lubrani, Miguel Angel Pérez Lorenzo, Alexander Dorta Fumero and Manuel Villegas Díaz, Operational validation of the OPTAIN-SA Tool. Supporting optimized profile descent approach sequencing into Palma TMA; in 2018 International Conference on Research in Air Transportation (ICRAT), URL http://www.icrat.org/icrat/8th-international-conference/papers/

# 10 Nomenclature

$C_d$= coefficient of drag

$C_l$= coefficient of lift

$D$ = drag force

$g$ = gravity acceleration

$h$= altitude

$L$ = lift force

$m$ = mass

$p$ = atmospheric pressure

$p_0$= standard value at sea level for atmospheric pressure

t = time

$T$ = thrust

$V$ = true airspeed

$x$ = longitudinal position

$\eta$ = thrust specific fuel flow

$\gamma$ = flight path angle

$\rho$ = atmospheric density

$\rho_0$= standard value at sea level for atmospheric density

$\tau$ = temperature

$\tau_0$= standard value at sea level for temperature

# 11 Abbreviations and acronyms

| Abbreviations & Acronym | Description |
|---|---|
| ACC | Area Control Centers |
| ACDM | Airport-Collaborative Decision Making |
| ANSP | Air Navigation Service Provider |
| ASBU | Aviation System Block Upgrades |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATS | Air Traffic Services |
| A319 | Airbus 319 |
| A330 | Airbus 330 |
| BADA | Base of Aircraft DAta |
| BARDI2K | BARDI TWO KILO |
| BARDI2T | BARDI TWO TANGO |
| BM1 | Boeing Method 1 |
| BM2 | Boeing Method 2 |
| BPBS | Best-Planned-Best-Served |
| CARATS | Collaborative Actions for Renovation of Air Traffic Systems |
| CCO | Continuous Climb Operation |
| CCS1K | CÁCERES ONE KILO |
| CCS1T | CÁCERES ONE TANGO |
| CDO | Continuous Descent Operation |
| CGL | Chebyshev-Gauss-Lobatto |
| DAE | Differential Algebraic system of Equations |
| DME | Distance Measuring Equipment |
| DNAP | Departure Noise Abatement Procedures |
| DOF | Degree Of Freedom |
| DVOR | Distance VHF Omnidirectional Radio Range |
| ECI | Earth-Centered Inertial |
| FCFS | First-Come-First-Served |
| FDR | Flight Data Recorder |
| FF | Fuel Flow |
| FF-ICE | Flight and Flow Information in a Collaborative Environment |
| ft | feet |
| FL | Flight Level |
| fpm | Feet per minute |
| FTS | Fast Time Simulation |
| GANP | Global Air Navigation Plan |
| GW | Gross Weight |
| IAS | Indicated Air Speed |
| ICAO | International Civil Aviation Organization |
| ICRAT | International Conference for Research in Air Transportation |
| INM | Integrated Noise Model |
| IPOPT | Interior Point Optimizer |

| | |
|---|---|
| ISA | ICAO Standard Atmosphere |
| KPA | Key Performance Area |
| Kg | Kilogram |
| Kt | Knots |
| LEMD | Adolfo Suárez Madrid-Barajas airport |
| MCG | Minimum Climb Gradient |
| NLP | Non-Linear Program |
| NextGen | Next Generation Air Transportation System |
| Nm | Nautical Mile |
| NPD | Noise-Power-Distance |
| NPR | Noise Preferred Route |
| OCP | Optimal Control Problem |
| OPD | Optimal Descent Approaches |
| OPTA | Optimized Profile Descent Approaches |
| OPTAIN | Optimized Profile Descent Approaches–Implementing Windows |
| pp | engine thrust settings |
| PBN | Performance Based Navigation |
| PMI | Palma de Mallorca Airport |
| ROC | Rate of Climb |
| RECAT-EU | European Wake Vortex Re-Categorization |
| RTS | Real Time Simulation |
| RWY | Runway |
| SESAR | Single Sky ATM Research |
| SID | Standard Instrument Departure |
| SJU | Sesar Joint Undertaken |
| STAR | Standard Arrival Route |
| TAS | True Air Speed |
| TOBT | Target of Block Time |
| TMA | Terminal Maneuvering Areas |
| TLP | Thrust Level Percentage |
| TOW | Take-off Weight |
| TTOT | Target Take-off Time |
| V | Velocity |
| WPT | Waypoint |

# 12 Reference documents

Other documents which should be referred to;


[1] Solar Impulse SA. Solar impulse clean technologies to fly around the world (2019). URL http://aroundtheworld.solarimpulse.com

[2] ICAO, The Global Air Navigation Plan portal, International Civil Aviation Organization, 999 University Street, Montréal, Canada (2019) URL https://www4.icao.int/ganpportal/.

[3] SESAR, Single sky atm research (2019). URL http://www.sesarju.eu.

[4] NextGen, The next generation air transportation system (2019). URL https://www.faa.gov/nextgen/

[5] CARATS, Collaborative Actions for Renovation of Air Traffic Systems. (2019). Retrieved from http://www.mlit.go.jp/en/koku/koku_fr13_000000.html

[6] ICAO, Continuous Climb Operations (CCO) Manual (Doc.9993), International Civil Aviation Organization, 999 University Street Montréal, Quebec, Canada, 1st Edition (2013).

[7] H. G. Visser, S. Hartjes, Economic and environmental optimization of flight trajectories connecting a city-pair, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering.

URL http://pig.sagepub.com/content/early/2013/07/02/0954410013485348.abstract .

[8] Turgut, E. T., & Usanmaz, O. (2013). NOx, fuel consumption and time effects of flight path angle during descent. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 227 (5) (2013) 737-750.

URL http://pig.sagepub.com/content/227/5/737.

[9] S. Alam, M. H. Nguyen, H. Abbass, C. Lokan, M. Ellejmi, S. Kirby. (2010). A Dynamic Continuous Descent Approach Methodology for Low Noise and Emission. AIAA/IEEE Digital Avionics Systems Conference – Proceedings (2010) 1.E.5-1doi:10.1109/DASC.2010.5655502.

[10] Eurocontrol, Airport Collaborative Decision-Making (CDM) Implementation Manual, version 5.0, European Organisation for the Safety of Air Navigation, EUROCONTROL Agency Rue de la Fusee, 96 B -1130 BRUXELLES (2017).

[11] ICAO, Manual on Global Performance of the Air Navigation System (Doc.9883), International Civil Aviation Organization, 999 University Street Montréal, Quebec, Canada, 1st Edition (2009).

[12] D. McConnachie, P. Bonnefoy, and A. Belle, Investigating benefits from continuous climb operating concepts in the national airspace system, in: FAA/EUROCONTROL (Ed.), Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), no. 501, FAA/EUROCONTROL, 2015.

[13] ICAO, Continuous Descent Operations (CDO) Manual (Doc. 9931), International Civil Aviation Organization, 999 University Street Montréal, Quebec, Canada, 1st Edition (2010).

[14] ICAO, Procedures for Air Navigation Services - Aircraft Operations (PANS-OPS) (Doc. 8168), International Civil Aviation Organization, 999 University Street Montreal, Quebec, Canada, 5th Edition (2006).

[15] S. Hartjes, H. G. Visser, S. J. Hebly, Optimization of rnav noise and emission abatement departure procedures, in: 9th AIAA Aviation Technology, 500 Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS), 2009, p. 6953.

[16] DA1 - OPTA-IN Demo Project 01.08 Validation Plan, SESAR Integrated Flight Trials and Demonstration Activities, SESAR Joint Undertaking (2014).

[17] DA2 - OPTA-IN Demo Project 01.08 - Validation Report, SESAR Integrated Flight Trials and Demonstration Activities, SESAR Joint Undertaking (2014).

[18] OPTA Final Report July, ENAIRE (former Aena) (2012).

[19] Peter Lubrani, Miguel Angel Pérez Lorenzo, Alexander Dorta Fumero and Manuel Villegas Díaz, Operational validation of the OPTAIN-SA Tool. Supporting optimized profile descent approach sequencing into Palma TMA; in 2018 International Conference on Research in Air Transportation (ICRAT), URL http://www.icrat.org/icrat/8th-international-conference/papers/

[20] Erzberger, H. and Lee, H., Constrained optimum trajectories with specified range, Journal of Guidance, Control, and Dynamics, Vol. 3, No. 1, 1980, pp. 78–85. doi:10.2514/3.55950. URL http://dx.doi.org/10.2514/3.55950

[21] M. Soler-Arnedo, A. Olivares, E. Staffetti, Hybrid Optimal Control Approach to Commercial Aircrafts 3D Multiphase Trajectory Optimization, American Institute of Aeronautics and Astronautics, 2010. doi:doi: 10.2514/6.2010-8453. URL https://doi.org/10.2514/6.2010-8453

[22] M. Soler, A. Olivares, E. Staffetti, D. Zapata, Framework for aircraft trajectory planning toward an efficient air traffic management, Journal of Aircraft 49 (1) (2012) 341–348. doi:10.2514/1.C031490. URL http://arc.aiaa.org/doi/abs/10.2514/1.C031490

[23] P. Bonami, A. Olivares, M. Soler, E. Staffetti, Multiphase mixed-integer optimal control approach to aircraft trajectory optimization, Journal of Guidance, Control, and Dynamics 36 (5) (2013) 1267–1277. doi:10.2514/ 1.60492. URL https://doi.org/10.2514/1.60492

[24] M. Soler, A. Olivares, E. Staffetti, Multiphase optimal control framework for commercial aircraft four-dimensional flight-planning problems, Journal of Aircraft 52 (1) (2014) 274–286. doi:10.2514/1.C032697. URL https://doi.org/10.2514/1.C032697

[25] D. González-Arribas, M. Soler, M. Sanjurjo-Rivo, Robust aircraft trajectory planning under wind uncertainty using optimal control, Journal of Guidance, Control, and Dynamics 41 (3) (2017) 673–688. doi:10.2514/ 1.G002928. URL https://doi.org/10.2514/1.G002928

[26] R. E. Bellman, Dynamic Programming, Princeton UP, 1957.

[27] P. E. Gill, W. Murray, M. H. Wright, Practical Optimization, Academic Press,1981.

[28] J. Nocedal, S. J. Wright, Numerical Optimization, Springer Verlag, 1999

[29] L. Pontryagin, V. Boltyanskii, R. Gamkrelidze, E. Mishchenko, The Mathematical Theory of Optimal Processes, Interscience Publishers, 1962.

[30] D. Garg, M. Patterson, W. Hager, A. Rao, D. Benson, G. Huntington, A unified framework for the numerical solution of optimal control problems using pseudospectral methods, Automatica 46 (11) (2010) 1843–1851.
URL https://doi.org/10.1016/j.automatica.2010.06.048

[31] C. Canuto, M. Y. Hussaini, A. Quarteroni, T. A. Zang, Spectral methods:: Fundamentals in single domains, Springer-Verlag Berlin Heidelberg, 2006.

[32] R. Z. Jiang Zhao, X. Jin, Reentry trajectory optimization based on a multistage pseudospectral method, The Scientific World Journal vol. 2014 (878193) (2014) 13.

[33] F. Fahroo, I. M. Ross, Direct trajectory optimization by a chebyshev pseudospectral method, Journal of Guidance, Control, and Dynamics 25 (1) (2002) 160–166. doi:10.2514/2.4862. URL http://arc.aiaa.org/doi/abs/10.2514/2.4862

[34] J. García-Heras, M. Soler, F. J. Sáez, A comparison of optimal control methods for minimum fuel cruise at constant altitude and course with fixed arrival time, Procedia Engineering 80 (2014) 231–244. doi:http://dx.doi.org/10.1016/j.proeng.2014.09.083.
URL http://www.sciencedirect.com/science/article/pii/ S187770581401176X

[35] AMPL, Ampl modeling language (2013) [cited Sep. 2019]. URL http://ampl.com

[36] Eurocontrol, User Manual for the Base of Aircraft Data (BADA) family 4, European Organisation for the Safety of Air Navigation, EUROCONTROL Agency Rue de la Fusee, 96 B - 1130 BRUXELLES (2014).

[37] ICAO, Manual of the ICAO Standard Atmosphere, International Civil Aviation Organization, 999 University Street, Montréal, Canada, 3rd Edition (1993).

[38] Prats, X., Puig, V., & Quevedo, J. (2011). A multi-objective optimization strategy for designing aircraft noise abatement procedures. Case study at Girona airport. Transportation Research Part D: Transport and Environment, 16(1), 31–41. doi:10.1016/j.trd.2010.07.007

[39] D. Mitchell, H. Ekstrand, X. Prats, T. Gronstedt, An environmental assessment of air trac speed constraints in the departure phase of flight: A case study at gothenburg landvetter airport, Sweden, Transportation Research Part D: Transport and Environment 17 (8) (2012) 610–618. doi:http://dx.doi.org/10.1016/j.trd.2012.07.006.

URL http://www.sciencedirect.com/science/article/pii/ S136192091200079X.

[40] A. Filippone, Aircraft noise prediction, Progress in Aerospace Sciences 68 (2014) 27 – 63. doi:http://dx.doi.org/10.1016/j.paerosci.2014. 02.001.

URL http://www.sciencedirect.com/science/article/pii/ S0376042114000311.

[41] E. R. Boeker, E. Dinges, B. He, G. Fleming, C. J. Roof, P. J. Gerbi, A. S. Rapoza, J. Hemann, Integrated noise model (inm) version 7.0 technical manual, FAA-AEE-08-01 NSN 7540-01-280-550 , U.S. Department of Transportation, Federal Aviation Administration, Oce of Environment and Energy 800 Independence Avenue, S.W. Washington, DC 20591 (January 2008).

[42] Olmstead, Jeffrey R., Fleming, Gregg G., Gulding, John M., Roof, Christopher J., Gerbi, Paul J., & Rapoza, Amanda S. 2002 (Jan). Integrated noise model (INM) version 6.0 technical manual. Federal Aviation Administration. Office of Environment and Energy., Washington, DC. USA. FAA-AEE-02-01.

[43] Turgut, E. T., Usanmaz, O., & Cavcar, M. (2018). The effect of flight distance on fuel mileage and CO2 per passenger kilometer. International Journal of Sustainable Transportation, 0(0), 1–11. doi: 10.1080/15568318.2018.1459970

URL https://doi.org/10.1080/15568318.2018.1459970

[44] Steven, S. C. H., Baughcum, L., Tritz, T. G., & Pikket, D. C. (April, 1996b). Scheduled civil aircraft emissions inventories for 1992: Database development and analysis, Appendix D: Boeing method 2 fuel flow methodology description, Tech. rep., NASA Contractor Report 4700.

[45] Chen, D., Hu, M., Han, K., Zhang, H., & Yin, J. (2016). Short/medium-term prediction for the aviation emissions in the en route airspace considering the fluctuation in air traffic demand. Transportation Research Part D: Transport and Environment, 48, 46–62. doi:10.1016/j.trd.2016.08.003

URL http://www.sciencedirect.com/science/article/pii/S1361920916301122

[46] Steven, S. C. H., Baughcum, L., Tritz, T. G., & Pikket, D. C. (April, 1996a). Scheduled civil aircraft emissions inventories for 1992: Database development and analysis, Appendix C: Boeing method 1 fuel flow methodology description, Tech. rep., NASA Contractor Report 4700.

[47] ICAO, Annex 11 to the Convention on International Civil Aviation - Air Traffic Services, International Civil Aviation Organization, 999 University Street Monteal, Quebec, Canada, 13th Edition (2001).

[48] M. Z. Li and M. S. Ryerson, A data-driven approach to modeling high-density terminal areas: a scenario analysis of the new Beijing, China airspace, Chinese Journal of Aeronautics, vol. 30, no. 2, pp. 538–553, 2017.

URL http://www.sciencedirect.com/science/article/pii/S1000936117300213

[49] ICAO, Manual on Collaborative Air Traffic Flow Management (Doc. 9971), International Civil Aviation Organization, 999 University Street Montréal, Quebec, Canada, 3rd Edition (2018).

[50] Ball, M.; Barnhart, C.; Dresner, M.; Hansen, M.; Neels, K.; Odoni, A.; Peterson, E.; Sherry, L.; Trani, A.A.; Zou, B. Total Delay Impact Study: A Comprehensive Assessment of the Costs and Impacts of Flight Delay in the United States; National Center of Excellence for Aviation Operations Research: Washington, DC, USA, 2010; pp. 50–56.

[51] Allahverdi A, Ng CT, Cheng TCE, Kovalyov MY. A survey of scheduling problems with setup times or costs. European Journal of Operations Research 2008; 187(3):985–1032. doi:https://doi.org/10.1016/j.ejor.2006.06.060.

URL http://www.sciencedirect.com/science/article/pii/ S0377221706008174

[52] Atkin JAD, Burke EK, Greenwood JS, Reeson D. Hybrid metaheuristics to aid runway scheduling at London Heathrow airport. Transportation Science 2007; 41(1):90–106. doi:10.1287/trsc.1060.0163.

[53] Atkin JAD, Burke EK ,Greenwood JS, Reeson D. On-line decision support for take-off runway scheduling with uncertain taxi times at London Heathrow airport. Journal of Scheduling 2008; 11(1):323–46.

[54] Atkin JAD, Maere GD, Burke EK, Greenwood JS. Addressing the pushback time allocation problem at Heathrow airport. Transportation Science 2013; 47(4):584–602.

[55] Kotynek B, Richetta O. Equitable models for the stochastic ground-holding problem under collaborative decision-making. Transportation Science 2006; 40(1):133–46.

[56] Kuhn KD. Ground delay program planning: delay, equity, and computational complexity. Transportation Research Part C 2013; 35(1):193–203.

[57] Manley B, Sherry L. Analysis of performance and equity in ground delay programs. Transportation Research—Part C2010; 18(6):910–20.

[58] Marcella Samà, Andrea D'Ariano, Paolo D'Ariano, Dario Pacciarelli, Scheduling models for optimal aircraft traffic control at busy airports: Tardiness, priorities, equity and violations considerations, Omega, Volume 67, 2017, Pages 81-98, ISSN 0305-0483, https://doi.org/10.1016/j.omega.2016.04.003.

[59] ICAO, Manual on Flight and Flow Information for a Collaborative Environment (FF-ICE) (Doc. 9965), International Civil Aviation Organization, 999 University Street Montreal, Quebec, Canada, 1st Edition (2012).

[60] Sureshkumar Chandrasekar, Inseok Hwang, T Algorithm for Optimal Arrival and Departure Sequencing and Runway Assignment D 2015 J Journal of Guidance, Control, and Dynamics, P 601-613, V 38 N 4 R 10.2514/1.G000084 https://arc.aiaa.org/doi/abs/10.2514/1.G000084.

[61] Eurocontrol, European Wake Vortex Re-Categorization (RECAT-EU) project, European Organisation for the Safety of Air Navigation, EUROCONTROL Agency Rue de la Fusee, 96 B - 1130 BRUXELLES (2017).

# Appendix A: Standard Instrument Departures (SID) – Madrid-Adolfo Suárez Madrid-Barajas 36L