Quantifying Vertical Descent Inefficiencies for Arrivals in Constrained Airspace: A Case Study at Schiphol Airport

Julia Huigen | Master of Science Thesis Aerospace Engineering

TU Delft

knowledge &
development
centre
Mainport Schiphol

Quantifying Vertical Descent Inefficiencies for Arrivals in Constrained Airspace: A Case Study at Schiphol Airport

Thesis report

by

Julia Huigen

to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on 27th of March, 2026 at 09:00

Thesis committee:	
Chair:	Dr.ir. J. (Joost) Ellerbroek - TU Delft
Supervisors:	Dr.ir. MJ (Marta) Ribeiro - TU Delft Dr.ir. J. (Junzi) Sun - TU Delft Ferdinand Dijkstra - KDC
External examiner:	Dr.ir. P. (Pieter-Jan) Proesmans - TU Delft
Place:	Faculty of Aerospace Engineering, Delft
Project Duration:	June, 2025 - March, 2026
Student number:	4867874

Coverpage image: Daniel Garrido | Getty Images [1]

Faculty of Aerospace Engineering · Delft University of Technology

Preface

With this master's thesis, my journey as an Aerospace Engineering student comes to an end. It has been an interesting and sometimes challenging journey.

This research was completed in collaboration with Luchtverkeersleiding Nederland (LVNL) through the Knowledge Development Centre Mainport Schiphol (KDC), allowing me to carry out this work close to real-world air traffic operations. When starting this project, I had little idea where it would lead and spent many conversations discussing the direction of the research with people around me. Like other long projects, this thesis had its challenges. During this process, I was reminded how lucky I am to have the support of the people around me, including both of my grandmothers, who are still here to see this moment.

During this master's programme, there were moments when I questioned why I had chosen this path and whether I belonged in this field. In the end, I realised that what brought me here was the desire to challenge myself and to see how far I could push my own capabilities. Completing this thesis has reminded me that perseverance and determination can lead further than expected.

With this chapter completed, I look forward to the next stage. I hope to follow a path where I can work on topics that I find both challenging and enjoyable, and where curiosity and enthusiasm remain the main driving forces.

I would like to thank my supervisor at LVNL, Ferdinand, for the many conversations we had throughout this project. Although we often discussed topics beyond the scope of the thesis, those discussions were always insightful, energetic, and honest. Your passion for the world of Air Traffic Management is inspiring, and it has been a pleasure to work with you. I hope we will continue those conversations in the future, perhaps over an ice cream.

Next, I would like to thank my TU Delft supervisors, Marta and Junzi, for your guidance and for the discussions that helped me move forward whenever I felt uncertain about the direction of my work. I appreciate the time and effort you invested in supporting this project and for sharing your academic insight throughout the process.

Finally, I would like to thank my friends and family for their continuous support, not only during the thesis but throughout my studies. Also, everyone at iLabs, thank you for all the discussions, collaborations, and shared struggles throughout this period. And Evert, for your helpful insights and fun conversations.

I am grateful to have reached this point and proud to say, "I made it."

Julia Huigen
March 2026, Delft

Contents

Nomenclature

List of Abbreviations

ACARS	Aircraft Communications and Reporting System
ACMS	Aircraft Condition Monitoring System
ADS-B	Automatic Dependent Surveillance–Broadcast
ADS-C	Automatic Dependent Surveillance–Contract
AIP	Aeronautical Information Products
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
BADA	Base of Aircraft Data
CAS	Calibrated Airspeed
CCO	Continuous Climb Operation
CDO	Continuous Descent Operation
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPDLC	Controller-Pilot Data Link Communications
DDR	Demand Data Repository
FANS	Future Air Navigation System
FIR	Flight Information Region
FMS	Flight Management System
FPA	Flight Path Angle
FRA	Free-Route Airspace
IAF	Initial Approach Fix
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
KPI	Key Performance Indicator
LoA	Letter of Agreement
LVNL	Luchtverkeersleiding Nederland
PBN	Performance-Based Navigation
RAD	Route Availability Document
RNAV	Area Navigation
RNP	Required Navigation Performance
SSR	Secondary Surveillance Radar
STAR	Standard Terminal Arrival Route
TBO	Trajectory-Based Operation
TOD	Top of Descent
VHF	Very High Frequency

Part I

Scientific Article

Quantifying Vertical Descent Inefficiencies for Arrivals in Constrained Airspace: A Case Study at Schiphol Airport

Julia Huigen[*] [†]
Supervised by Dr.ir. Marta Ribeiro[*], Dr.ir. Junzi Sun[*], Ferdinand Dijkstra[†]

[*]Faculty of Aerospace Engineering, Delft University of Technology (TU Delft), the Netherlands
[†] KDC - Knowledge and Development Center Mainport Schiphol, the Netherlands

Abstract—**Continuous Descent Operations (CDOs) can reduce fuel consumption and CO_2 emissions. However, their implementation in constrained airspace is often limited by operational procedures and altitude restrictions. Previous studies have evaluated CDO performance under idealised conditions, resulting in insufficient quantification of the effects of real operational constraints. This study investigates how operational constraints on arrival routes influence aircraft vertical descent profiles and the resulting fuel consumption. A framework is introduced that is capable of quantifying fuel consumption across different descent trajectories. The simulation-based framework enables the analysis of incremental modifications to operational restrictions, including changes to level-off altitude and duration. The methodology is applied to arrival traffic at Schiphol Airport, using a dataset of over 8,000 recorded arrivals from the Aircraft Condition Monitoring System (ACMS) and one month of Eurocontrol Demand Data Repository (DDR) traffic data. Level-off segments between Top of Descent (TOD) and the Initial Approach Fix (IAF) are identified and linked to waypoint-based restrictions specified in Letters of Agreement (LoAs) and the Route Availability Document (RAD). The BlueSky air traffic simulator and the Base of Aircraft Data (BADA) 3.16 performance model are used to quantify the fuel impact of modified descent scenarios. The results show a clear relationship between level-off duration, altitude constraints, and fuel consumption. Higher level-off altitudes and shorter durations consistently reduce fuel burn. Regression analysis of recorded flights confirms these trends. A Key Performance Indicator (KPI) based route assessment identifies arrival routes with the greatest potential to reduce fuel consumption, while taking into account operational complexity. The findings show that measurable fuel savings can be achieved through targeted adjustments in airspace restrictions without requiring a complete redesign of the airspace.**

I. INTRODUCTION

THE aviation industry contributes to global greenhouse gas emissions, and its environmental impact is expected to grow as air traffic continues to increase. To reduce or limit environmental impact, initiatives such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aim to achieve carbon-neutral growth in international aviation by encouraging airlines to adopt more fuel-efficient operations and invest in carbon-reduction projects [1], [2]. Furthermore, the International Air Transport Association (IATA) goal is to achieve net-zero emissions by 2050, with a 45 % reduction targeted by 2030 [3]. To achieve these targets, improvements are needed across multiple areas, including aircraft technology, alternative fuels, and operational efficiency. This research focuses on the last part: enhancing the efficiency of current flight operations.

One of the main areas where operational inefficiencies occur is during the descent phase of flight. Previous research has shown that CDOs can reduce fuel consumption and CO_2 emissions by allowing aircraft to descend with minimal thrust and without intermediate level-offs. These benefits are well established under ideal conditions and have also been shown in more complex airspace environments. However, in real operations, aircraft are often constrained by airspace structure, procedures, and operational agreements between air traffic service (ATS) providers. As a result, aircraft often cannot fly their optimal vertical profiles and instead perform stepped descents. These additional level-off segments increase fuel burn and CO_2 emissions.

Although the environmental benefits of CDOs are clear, the effects of specific operational constraints on vertical descent performance remain only partly quantified. In particular, the role of waypoint restrictions, sector-related procedures, and ATS agreements in causing vertical inefficiencies requires further investigation. In addition, many previous studies rely on idealised simulations or lower-fidelity surveillance data, which limits the assessment of real-world operational constraints and fuel impact. Therefore, this thesis investigates how specific constraints on arrival routes to Schiphol Airport affect aircraft vertical flight profiles and how modifying these constraints affects fuel consumption. The goal is to analyse these inefficiencies in detail and quantify them in terms of fuel consumption. The project also focuses on identifying where these inefficiencies are most significant, which Schiphol Airport arrivals are most affected, and where the greatest potential for improvement lies.

This paper is structured as follows. First, the background information is discussed in Section II, followed by the literature review in Section III. The methodology is described in Section IV. Section V describes how the method is applied to the selected use case, with Section VI explaining the experimental setup. Section VII presents the results, which are discussed in Section VIII. Future work is presented in Section IX. Finally, the conclusions are drawn in Section X.

II. BACKGROUND INFORMATION

This section provides the background information required for this research. It introduces CDOs in Subsection II-A, details Trajectory-Based Operations (TBO) in Subsection II-B, and then provides an overview of current technologies supporting trajectory management in Subsection II-C. Finally, in Subsection II-D operational agreements between Air Navigation Service Providers (ANSPs), documented in LoAs and RAD, are described.

A. Continuous Descent Operations (CDO)

CDO is an aircraft operating technique where an arriving aircraft descends continuously at its most optimal trajectory from the TOD to the initial or final approach fix [4], [5]. The TOD is calculated by the Flight Management System (FMS), extending the cruise phase and delaying the TOD to allow an idle-thrust or a fixed flight path angle trajectory with low power and low drag configurations [6], [7]. CDOs aim to reduce vertical inefficiencies by removing level-off segments, which are typical in step-down approaches used to maintain aircraft separation [2], [8]. These different approaches are depicted in Figure 1 To allow CDOs to be flown in congested airspace, such as the Dutch airspace, TBO is needed. When integrated into TBO, CDOs can reduce fuel consumption, emissions, and controller workload [9].

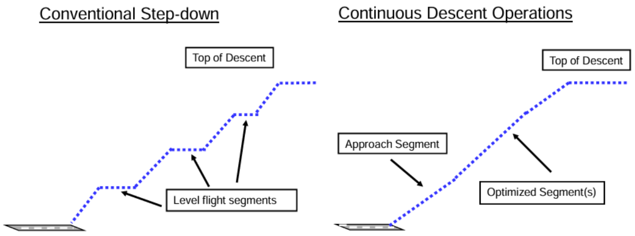


Fig. 1. Step Down Approach Compared to CDO [10]

B. Trajectory-Based Operations (TBO)

TBO is a concept for managing an aircraft's trajectory in four dimensions: latitude, longitude, altitude, and time [11]. It aims to improve predictability and efficiency in air traffic management (ATM) by enabling precise coordination between aircraft and air traffic controllers (ATCOs) [8]. At the moment, several airspace constraints exist in air traffic operations to ensure the safety of traffic flows. Under these airspace constraints fall restrictions such as agreements with neighbouring Flight Information Regions (FIR), handover constraints from and to ATCOs or capacity constraints. Most constraints and procedures are required because aircraft positions are not known with sufficient accuracy in all four dimensions. In addition, delays and unexpected disturbances often cause irregular traffic that is difficult to predict and manage. These limitations show the need for more accurate trajectory management, which TBO aims to provide.

In TBO, flight trajectories are planned and approved before departure and can be updated dynamically as conditions change [2]. This allows aircraft to fly optimal descent profiles that minimise fuel burn and emissions while maintaining safe sequencing and separation. In addition to real-time flight management, the efficient implementation of CDOs in TBO depends on several technologies that improve navigation accuracy and trajectory predictability. The most important technologies for this are Performance-Based Navigation (PBN), surveillance technologies such as Secondary Surveillance Radar (SSR) Mode S and Automatic Dependent Surveillance-Contract (ADS-C), and advanced FMS capabilities that support four-dimensional trajectory management. In addition, trajectory-based operations require communication technologies that enable the structured exchange of trajectory and intent information between air and ground.

C. Current Technologies

PBN defines the navigation performance required for aircraft operating within specific procedures or airspaces [12]. It standardises Area Navigation (RNAV) and Required Navigation Performance (RNP) specifications, reducing the number of different navigation procedures [13]. Through PBN, aircraft can follow more precise lateral paths and make more efficient use of available airspace. This accuracy supports the execution of CDOs by reducing the need for level-off segments and enabling continuous descent paths [2], [14]. Without PBN, accurate vertical and lateral trajectory optimisation, required for CDOs, would not be feasible.

For surveillance, ATC uses radar to monitor aircraft positions and flight parameters [15]. In the Dutch airspace, Luchtverkeersleiding Nederland (LVNL) uses enhanced SSR Mode S for this purpose [16]. Mode S allows discrete addressing of individual aircraft transponders, enabling ground systems to interrogate specific aircraft instead of broadcasting general interrogation signals [15], [17]. In addition to aircraft identity and altitude, Mode S enhanced surveillance can downlink additional parameters such as ground speed, heading, and selected altitude to support improved traffic monitoring and operational safety. Although Mode S improves surveillance accuracy, it mainly provides information about the aircraft's current state and offers limited insight into its intended future trajectory. For TBO, insights into the planned trajectory are required to improve trajectory prediction and coordination between aircraft and ground systems.

ADS-C solves part of the limitations of radar by enabling the automatic downlink of aircraft state and intent information to an ATS unit under predefined surveillance contracts between ATS units and aircraft operators [18], [19]. By providing projected trajectory information, ADS-C increases the accuracy of ground-based trajectory prediction and planning tools [20]. The addition of intent data improves the predictability of aircraft behaviour and supports the implementation of TBO.

Four-dimensional trajectory management refers to the planning and implementation of aircraft trajectories in four dimensions: the three-dimensional spatial position and time [9], [21]. The FMS is the onboard automation system responsible for trajectory planning [22]. An important feature of the FMS is the determination of the optimal TOD, which enables idle thrust descent profiles if procedures and airspace constraints allow it [5]. The FMS computes this based on parameters such as aircraft weight, weather conditions, and performance data, also taking into account speed, altitude, and time restrictions set by Air Traffic Control (ATC) or PBN specifications. FMS predictions are limited by onboard data availability and do not always reflect all current airspace constraints. This makes coordinated trajectory management between airborne and ground systems necessary to achieve predictable and efficient operations.

Such coordination depends not only on navigation and surveillance capabilities, but also on reliable communication between aircraft and ATC. The main means of communication in ATM remains voice communication using Very High Frequency (VHF) in most cases [23]. Even though voice communication is flexible, it limits the ability to support trajectory-based concepts at increased scales and increases controller and pilot workload as air traffic grows. To reduce dependence on voice communication, datalink services enabled digital exchange between aircraft and ATC. Controller-Pilot Data Link Communications (CPDLC) provides two-way datalink for sending standardised digital messages such as clearances, requests, and instructions [15], [24]. The Future Air Navigation System (FANS) concept introduced the use of CPDLC in combination with ADS-C surveillance for optimised communication, surveillance integration, and 4D navigation [25], [26]. However, FANS is limited by the low bandwidth of the Aircraft Communications and Reporting System (ACARS) network and the structure of ADS-C messages [20]. This limits how much trajectory intent and state information can be exchanged in real time.

These technologies support TBO by improving navigation accuracy, surveillance quality, onboard trajectory prediction, and air–ground information exchange. Together, these technologies allow aircraft to operate more freely with greater predictability and support the implementation of CDOs. However, despite these improved technological capabilities, the potential benefits of improved descent operations remain constrained by existing airspace structure, procedures and restrictions.

D. *Letters of Agreement (LoAs) and Implementation*

Technological improvements alone are not enough to enable fully optimised operations with CDOs. Coordination between ATS plays a significant role. Current LoAs between ATS define, for example, transfer points and altitude restrictions. In many cases, these restrictions limit the ability to maintain an optimal vertical flight profile. The European Continuous Climb and Descent Operations Action Plan, a collaboration with European aviation stakeholders, has the objective to significantly reduce CO_2. The initiative recommends regular reviews of LoAs to ensure that restrictions remain relevant. They also note that LoAs can benefit from the creation of new waypoints to facilitate a more optimal TOD or descent profile [27]. Effective collaboration between ATS units is therefore necessary to achieve the vertical efficiency goals expected through a TBO framework [28].

III. LITERATURE REVIEW

The environmental and operational benefits of CDOs have been established in various studies. However, their performance in constrained airspace is not yet completely understood. Various studies evaluate CDOs under idealised conditions and do not fully account for the combination of constraints present in high-density airspace, such as altitude restrictions, sector boundaries, sequencing requirements, speed control instructions, and coordination procedures defined in LoAs [2], [29]. As a result, reported fuel and emission reductions often represent theoretical potential rather than achievable operational performance. Similarly, several studies identify early TOD execution, level-offs, and stepped descents as main contributors to additional fuel burn during descent [5], [21], [30]. However, these inefficiencies are mainly quantified, while their underlying causes are not analysed in detail. The role of procedures, airspace structure, and operational constraints in creating vertical inefficiencies therefore remains insufficiently explained, and it remains unclear which constraints limit the implementation of CDOs the most.

Some airports have already shown that CDOs can be implemented in busy airspace environments. For example, at Frankfurt Airport, aircraft are required to fly CDOs through predefined Standard Terminal Arrival Routes (STARs) and optimised descent profiles [31]. The combination of fixed lateral routes and optimised vertical profiles allows arrival traffic to descend continuously while maintaining safe spacing between aircraft. Airlines operating at Frankfurt have reported significant reductions in fuel consumption through the implementation of these procedures. This example shows that, with appropriate operational procedures, CDOs can be implemented in congested airspace environments.

A second gap relates to the data sources used to assess descent efficiency. Several studies use surveillance data such as Automatic Dependent Surveillance-Broadcast (ADS-B) to analyse descent behaviour and estimate fuel consumption [6], [8]. ADS-B data can be suitable for large scale traffic analysis. However, ADS-B data does not provide information on aircraft mass, engine settings, or pilot and controller intent, and can contain inaccuracies. These limitations affect the accuracy of fuel and emissions estimates and restrict validation of model-based results. The use of high-fidelity data, such as ACMS data, remains limited in CDO research.

Recent research has highlighted the potential of advanced ATM concepts, such as TBO, to improve descent efficiency [21]. However, there is limited analysis of how such concepts could be applied incrementally within existing airspace structures. The impact of modifying individual airspace constraints on possible descent profiles and fuel consumption has not been quantified.

Overall, the literature indicates a need for research that combines high-fidelity flight data with a detailed representation of operational and airspace constraints to better understand descent inefficiencies under real-world conditions. Existing studies quantify contributors to inefficiency, such as early descents or level-off segments, but provide limited insight into the operational constraints that cause these inefficiencies. Also, the potential benefits of modifying specific airspace restrictions on achievable descent trajectories and fuel consumption remain insufficiently quantified. Addressing these gaps is necessary to identify realistic opportunities for improving vertical efficiency and enabling more effective implementation of CDOs in constrained airspace environments.

IV. METHODOLOGY

In this section, the methodology applied in this research is explained. First, an outline of the general approach is provided in Subsection IV-A to describe how the research is structured and which tools are used. Then, in Subsection IV-B, the simulation setup is described, including how real flight data and wind effects are implemented, and adjusted scenarios are created. After which, the BADA performance model and the fuel estimation of both recorded and simulated flights are detailed in Subsection IV-C and Subsection IV-D. Finally, the framework is detailed in Subsection IV-E.

To address the research gaps identified in the literature review, this study develops a simulation-based framework to quantify fuel consumption across different descent trajectories under operational constraints. The objective of this research is to determine how specific operational and airspace constraints affect vertical descent profiles and fuel consumption, and to assess how incremental modifications to these constraints influence descent efficiency. The framework combines high-fidelity flight data with trajectory simulation to analyse the impact of individual constraints on vertical flight performance. By allowing targeted adjustments to level-off altitudes and durations, the methodology enables the isolation and quantification of their contribution to fuel consumption. The approach is applied to arrival traffic at Schiphol Airport to identify routes and constraints where operational improvements may provide the largest environmental benefits.

A. Outline

In this research, a stepwise simulation-based methodology is followed to evaluate the impact of airspace procedures and constraints on vertical flight efficiency and fuel consumption. The approach compares current descent operations constrained by existing procedures and limitations, with incremental trajectory improvements enabled by TBO. These trajectories are created using adjusted flight scenarios and evaluated to assess the impact of the incremental adjustments. The methodology combines the open-source air traffic simulation environment BlueSky, the aircraft performance model BADA by Eurocontrol, for performance data such as fuel flow and real-world flight data for validation and analysis into current operations. Real-world flight data from the ACMS and the DDR will be used to analyse the sources of inefficiency in the Dutch airspace for arrival traffic to Schiphol Airport. Also, the current traffic loads and airspace use are analysed. These are reviewed and summarised by the KPIs. By modifying operational constraints, the influence of airspace limitations on fuel consumption can be quantified through simulations that address these inefficiencies.

B. Simulation

This research uses the open-source air traffic simulation environment, BlueSky, that models flight operations. For performance modelling in BlueSky, BADA 3.16 is used. Using recorded flight data from the ACMS, flights are reproduced in BlueSky to validate the simulator and the performance model's accuracy. These fuel validation simulations are essential to determine whether BlueSky can accurately replicate real-world flight trajectories and estimate fuel consumption. Once the simulator's reliability is confirmed, the results of changes to airspace constraints can be provided with greater confidence.

A simulation in BlueSky is based on a scenario which can be predefined using scenario files. An example of a scenario is presented in Appendix A. Scenarios are run in batches which is also explained in more detail in the Appendix B. In Figure 2, the flow of a BlueSky run from creation of the scenarios to saving the log files is depicted.

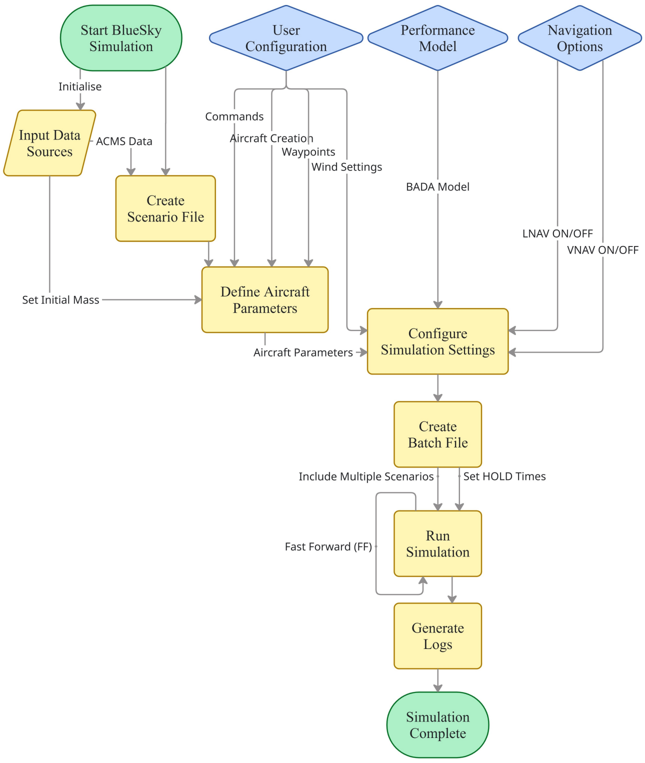


Fig. 2. Flowchart of the BlueSky Simulation Workflow from Scenario Creation and Configuration to Simulation Execution and Log Generation.

From the ACMS data a scenario for each flight is generated. Each scenario contains waypoints with a five-second time step to improve compatibility. For every waypoint, the latitude, longitude, altitude, and speed are included. The latitude and longitude are taken directly from the ACMS data and expressed in degrees on the WGS84 reference system, which BlueSky also uses for positioning. The altitude used is the pressure altitude, as the simulator uses International Standard Atmosphere (ISA) conditions for calculations. For speed, the Calibrated Airspeed (CAS) is used because it best reflects the aircraft's performance. The initial heading is obtained from the first ACMS record, using the recorded true heading value. Lastly, the aircraft's initial mass is derived from the ACMS data and used as input to the performance model to improve fuel performance output. The lateral and vertical navigation functions in BlueSky determine the flight path to the destination and simulate basic FMS behaviour.

To improve the resemblance between simulated and real-world trajectories, wind effects are included in the simulation. As exact meteorological data for the flights is not available and flights are anonymised, the wind vector is estimated directly from the recorded flight data. At each waypoint, the wind components are derived from the difference between the ground speed and true airspeed vectors obtained from the flight data. This provides an approximation of the wind experienced by the aircraft along its trajectory and captures short-term variations. The resulting wind vectors are added to the BlueSky scenario and applied during the simulation. This approach enables a more realistic reproduction of actual flight conditions and improves the accuracy of trajectory and fuel comparisons. The eastward and northward wind components are computed using Equations 1, 2, 3, and 4.

$$u_{\text{wind}} = GS_{\text{E}} - TAS_{\text{E}} \tag{1}$$

$$v_{\text{wind}} = GS_{\text{N}} - TAS_{\text{N}} \tag{2}$$

$$V_{\text{wind}} = \sqrt{u_{\text{wind}}^2 + v_{\text{wind}}^2} \tag{3}$$

$$\psi_{\text{wind}} = \tan^{-1}\left(\frac{u_{\text{wind}}}{v_{\text{wind}}}\right) + 180^\circ \tag{4}$$

Where u_{wind} and v_{wind} represent the eastward and northward wind components, respectively. GS_{E} and GS_{N} denote the aircraft ground speed in the east and north directions, while TAS_{E} and TAS_{N} represent the true airspeed components in the same directions. V_{wind} is the resulting wind speed magnitude, and ψ_{wind} is the wind direction.

All simulations are run in standard mode with a fixed time step of 0.5 seconds and fly-by waypoints to increase fidelity. The simulation log includes the aircraft's altitude, speed, position, fuel flow, and mass. The altitude and position are used to compare the simulated trajectories with the real ACMS data for compatibility. The accuracy of fuel consumption modelling is evaluated by comparing the simulated fuel consumption with recorded flight data. These comparisons determine whether BlueSky, when combined with the selected performance models, can accurately represent descents. Once the simulator's accuracy is determined, new simulations can be run with modified restricting waypoints to model changes in restrictions.

These modified scenarios are created by isolating the start and end of the level segments, with no additional points during the descent. Only level segments between TOD and the IAF are considered. These isolated segments are adjusted in altitude by increasing or decreasing the level segments' altitudes by 1000 and 2000 ft. Also, adjustments are made to the start of the level segment. This is done in 5-second increments up to 30 seconds. This will show a general trend in fuel consumption with respect to the altitude and duration change of level segments. The wind is still added for each waypoint.

C. Base of Aircraft Data (BADA)

The BADA model, developed by Eurocontrol, is a performance model that describes the aerodynamic and engine characteristics of various aircraft. It estimates thrust, fuel flow, and speed profiles under various flight conditions. BADA accounts for changes in aircraft mass during flight, which is important for realistic fuel consumption modelling [32]. BADA is a collection of data files in which operational performance parameters, airline procedures and overall performance are detailed [33]. Therefore, the BADA 3.16 files are integrated into BlueSky. With this combination, flight operations can be simulated with performance data. The integration uses the aircraft's initial mass, taken from the ACMS data, as input to improve fuel flow prediction, instead of the original value in the files.

D. Fuel Estimation

To evaluate the fuel consumption of different flights, it must be accurately estimated and calculated. For the simulated flights, this is done using the BADA aircraft performance model. For real flights, fuel consumption is calculated directly from the ACMS data and used to validate the simulation results. First, the fuel consumption calculation for the recorded flights is explained and secondly, for the simulated flights.

1) Fuel Consumption Recorded Flights: for the recorded flights, the fuel consumption is derived from the ACMS data, which contains the recorded fuel flow of each engine and total fuel quantity at different time steps. To calculate the overall fuel consumption, there are two possibilities. The difference in total fuel mass in the tank at the start and at the end of the flight and the integration of the total fuel flow over time [2]. The total fuel flow is calculated by Equation 5 in which the left and right engine fuel flows for each time step are summed:

$$FF_{total} = FF_{left}[i] + FF_{right}[i] \tag{5}$$

where FF_{total} represents the total fuel flow at time step i with $FF_{left}[i]$ as the fuel flow of the left engine at time step i, and $FF_{right}[i]$ the fuel flow of the right engine at time step i. The total fuel used during the descent is then calculated by integrating the fuel flow over time in Equation 6.

$$F = \sum_{i=1}^{N-1} \frac{FF_{total}[i]}{2} \cdot \Delta t_{hr} \tag{6}$$

where F represents the total fuel consumed during the analysed flight segment, $FF_{total}[i]$ is the total fuel flow at time step i, N is the total number of recorded time steps, and Δt_{hr} is the time interval between two consecutive measurements expressed in hours.

The time interval is defined as $\Delta t_{hr} = \frac{5}{3600}$ since the ACMS data are sampled every five seconds and fuel flow is recorded in kg/h. The integration is approximated using the trapezoidal rule, resulting in the total mass of fuel burned during the analysed flight segment, expressed in kg.

2) Fuel Consumption Simulated Flights: for the simulated flights, the fuel flow is an output variable from the BADA performance model and saved in the logfile after a simulation run. For jet engines, the thrust-specific fuel consumption is calculated as a function of true airspeed (TAS) in $knots$ presented in Equation 7:

$$\eta = C_{f1}\left(1 + \frac{V_{TAS}}{C_{f2}}\right) \tag{7}$$

where η denotes the thrust-specific fuel consumption, V_{TAS} is the true airspeed, and C_{f1} and C_{f2} are aircraft- and engine-specific fuel consumption coefficients provided in the BADA performance tables.

The nominal fuel flow is then obtained by Equation 8:

$$f_{nom} = \eta \cdot T \tag{8}$$

where f_{nom} represents the nominal fuel flow and T is the engine thrust. The thrust T is obtained from the Total Energy Model shown in Equation 9:

$$(T - D)\, V_{\text{TAS}} = mg\frac{dh}{dt} + mV_{\text{TAS}}\frac{dV_{\text{TAS}}}{dt} \tag{9}$$

where D denotes the aerodynamic drag, m is the aircraft mass, g is the gravitational acceleration, h is the aircraft altitude, and V_{TAS} is the true airspeed.

Under idle or descent conditions, the minimum fuel flow f_{min} is defined by Equation 10:

$$f_{min} = C_{f3}\left(1 - \frac{h}{C_{f4}}\right) \tag{10}$$

where f_{min} is the minimum fuel flow during idle or descent conditions, and C_{f3} and C_{f4} are aircraft- and engine-specific fuel consumption coefficients.

For cruise conditions, the fuel flow is calculated using Equation 11:

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

where f_{cr} represents the cruise fuel flow and C_{fcr} is a cruise fuel flow correction coefficient.

In the BlueSky output, the fuel flow is recorded for each time step. The total fuel consumption is then calculated using the same trapezoidal integration method as for the real flights, as shown in Equation 6. The only difference is that the fuel flow is given in kg/s, and the simulation time step is $\Delta t_{hr} = 0.5$.

E. Framework

The framework combines all aspects of the research and provides a clear structure for analysing how airspace procedures influence vertical flight efficiency. It is used to visualise the simulations and to organise and interpret the results. The aim of the framework is to show how operational restrictions, such as altitude or speed constraints, affect aircraft descent profiles. By changing these restrictions step by step, the results can be compared to assess the effects on fuel consumption. Furthermore, results can show if a descent profile can come closer to the ideal continuous descent profile. To build the framework, several components are needed:

- **Airspace structure**: an overview of the sectors, control areas, and the upper and lower limits of the Dutch and surrounding airspaces.
- **Waypoint data**: an overview of all waypoints present in the Dutch and surrounding airspaces.
- **Procedures and constraints information**: the position and type of current operational restrictions that limit vertical flight performance from the RAD by Eurocontrol, LoAs between different ATS provided by Eurocontrol and LVNL, and Aeronautical Information Products (AIP) by LVNL and ANSPs from surrounding countries.
- **Capacity data**: capacity of sectors that help assess how feasible each scenario would be in real operations.

All datasets are linked so that each flight in the simulation can be connected to the corresponding airspaces and restrictions it passes through in its trajectory, as well as the aircraft type. This setup enables analysis of how each constraint affects flight performance and comparison of different airspace capacities within the same framework. It also allows consistent comparison across scenarios and ensures that the results are realistic and highly accurate. A dashboard was created to aid the data analysis. A general overview of this dashboard is presented in the Appendix F.

The framework presents results including changes in the TOD position, potential fuel savings, and changes in sector crossings. In addition, a filtering function allows users to isolate specific aircraft types, arrival routes, or time periods for targeted analysis. This enables evaluation of how modifications to operational parameters affect descent performance and environmental outcomes.

The framework is designed to analyse how operational constraints influence vertical inefficiencies. Level-off segments are used as indicators of underlying constraints within the arrival procedures and airspace structure. These constraints may originate from, for example, altitude restrictions or sector handover agreements. By adjusting selected parameters, the framework evaluates how modifications to these constraints affect fuel consumption and TOD prediction.

The changeability factors considered in this research are:

1) Adjustment of the altitude of identified level segments
2) Modification of the start location of level segments
3) Combination of altitude and level-off start location changes
4) Variation in the proportion of flights applying adjusted routes

V. USE CASE

This section describes the use case to which the proposed method is applied. However, the method is not limited to this specific airport or airspace and can be applied to any airport with sufficient flight and airspace data. The selected use case defines the scope of this research, as described in Subection V-A. In Subsection V-B, the specific data that are used are detailed.

A. *Use Case Scope*

The use case is the arrival traffic at Schiphol Airport. In the Dutch airspace, these arrivals follow standard arrival routes, the STARs. These routes are shown in Figure 3. The analysed flights cover a set of arrivals at different times of day and throughout the year. The research focuses on the descent phase, starting from the cruise segment, some time before the TOD, and ending at the IAF. The approach phase, defined as the trajectory after the IAF, is not considered in this research. This is because ATCO sequencing and vectoring are irregular and do not convey information about airspace constraints. This research region is indicated in Figure 4.

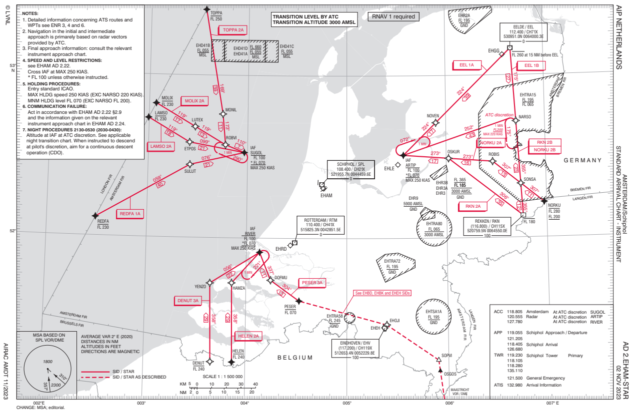


Fig. 3. STARs of Schiphol Airport [7]

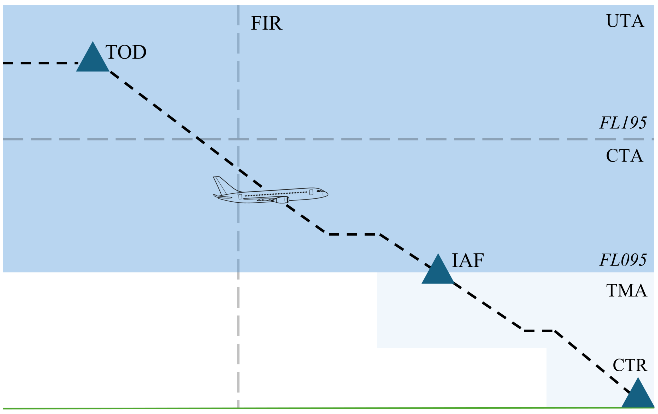


Fig. 4. Airspace Vertical Layout where the Darker Shaded Areas, the CTA and UTA, are the Main Focus of the Research, Until the IAF at FL100, where the TMA Starts at FL095

B. *Data Sources*

Several data sources are used to construct the simulation scenarios and to support the analysis. The primary data source is an ACMS dataset containing actual flight information on arrivals to Schiphol Airport. The dataset includes aircraft state and performance information sampled at a five-second interval. The dataset covers the descent phase from cruise until landing. The recorded parameters include position, altitude, ground speed, true airspeed, thrust, fuel flow, aircraft and engine types, and selected aircraft configuration parameters, such as flap settings and landing gear position.

To ensure reliable reproduction of descent trajectories, the dataset is filtered based on the destination airport, the availability of all required descent phases, and the removal of flights with abnormal altitude or horizontal position jumps or overall abnormal behaviour. In total, over 8000 arrival flights are included in the ACMS dataset, representing thirteen different aircraft types. The dataset is anonymised, so the exact dates and flight identifications are unknown.

In addition to the ACMS data, traffic and airspace information is obtained from the Eurocontrol DDR model 3 and supporting Eurocontrol datasets. DDR M3 data presents the flight plans enhanced with radar data [34]. This data represents all historical flights requested by identifying the amount of time and the departure and arrival airports, for example. Open waypoint databases and AIP are used to define the waypoint locations and published arrival procedures. One month of DDR traffic data is used to gain deeper insights into the dynamics of variability of traffic density. Flights crossing certain routes are used to identify possible adjustments to flight inefficiencies.

VI. EXPERIMENTAL SETUP

This section describes the experimental setup used to analyse the impact of operational constraints on vertical flight efficiency and fuel consumption. Together with the use case, they specify the analysis framework used for the research. First, the KPIs used to evaluate arrival route performance are presented in Subsection VI-A. Next, the assumptions and definitions applied throughout the analysis are described in Subsection VI-B.

A. *Key Performance Indicators (KPIs)*

The KPIs indicate the performance of Schiphol Airport arrival routes across various indicators. The outcome of this KPI analysis creates insights into the various arrival routes and identifies a focus for further research into possible operational improvement, where implementing the CDO or changing restrictions are effective and have a sufficient impact. The different arrival routes up to the IAF are analysed, as the level-offs and procedures below are mainly due to ATCO interventions rather than airspace constraints. The arrival routes are determined by LVNL, presented in the AIP, and depicted in Figure 3. The KPIs used to analyse the routes are explained in Table I. To the KPIs, weights are attached. A sensitivity analysis is performed to assess how variations in these weights influence the ranking of the arrival routes and to evaluate the robustness of the results.

The KPIs are chosen to identify the areas of interest for both the airlines and ATC and combined with KPIs usually used as ATM KPIs listed by the International Civil Aviation Organisation (ICAO) [35]. Moreover, the KPIs are selected to gain insights into route complexity and inefficiencies, and to determine where high-impact opportunities exist and where implementation is feasible. The level of impact was chosen as a KPI because the data are sensitive to the duration of a level segment and the level-off count. Therefore, combining them provides a better understanding of the true inefficiency in that route. A depiction of this sensitivity is presented in Figure 14 in Appendix C. Then, delta fuel is the difference in fuel consumption during level flight compared with the additional fuel burn during the extended cruise phase. Figure 5 shows how this comparison is made. Average sector counts and daily traffic are used to assess the route's complexity. Similarly, the maximum density and the number of flights in the sector indicate the maximum workload for ATC and thus contribute to a route's complexity.

TABLE I
KPI OVERVIEW FOR ATC AND AIRLINE STAKEHOLDERS WITH DESCRIPTION AND DISTRIBUTION OF WEIGHTS

	KPI	**Unit**	**Description & Dataset**	**Weight**
Airline	Average Level-Off Impact	[s·count level-offs]	Average time spent in level flight times the amount of level-offs below TOD and above 10,000 ft (ACMS)	0.2
	Delta Fuel	[kg/flight]	Additional fuel burn through addition of the fuel burn of the level segments and subtraction of additional fuel burn of the extended flight phase (ACMS)	0.2
	Sector Usage	[count sectors /flight]	Amount of sectors flown through per flight (ACMS)	0.1
	Traffic Density	[flights/ hour]	Average number of arrival flights flying this route per hour (DDR)	0.1
ATC	Maximum Traffic Density	[flights /hour]	Maximum traffic flying in the vicinity of the route at a certain moment in time (DDR)	0.2
	Maximum Capacity per Sector	[flights /hour]	Maximum number of aircraft simultaneously present in one sector at a certain moment in time (DDR)	0.2

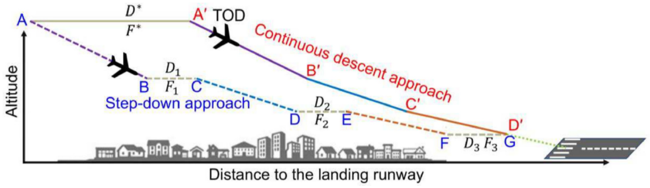


Fig. 5. Delta Fuel Calculated through Adding Fuel Consumption of the Level Segments (F_1, F_2, F_3) minus the Additional Fuel of the Extended Cruise Phase (F^*), ΔFuel $= F_1 + F_2 + F_3 - F^*$ [2]

B. Assumptions and Definitions

The assumptions and definitions enable consistent comparison between recorded flight data and simulated trajectories. Moreover, they enable the isolation of the effects of airspace constraints on vertical flight efficiency. Most importantly, the assumptions simplify the analysis. The assumptions used in this research are presented first, followed by some key definitions.

1) Fuel consumption for both ACMS and simulated flights was computed by trapezoidal integration of the modelled fuel flow at the time step. Fuel flow signals are assumed to be representative of total engine fuel use.
2) All flights are treated as independent trajectories.
3) No conflict detection or conflict resolution is applied in the simulations. This means that interactions between aircraft are neglected.
4) Traffic density indicators are derived from historical traffic data obtained from the DDR and are used only for KPI analysis. These traffic results are not used in the trajectory simulations themselves, solely for the purpose of density insights.
5) All altitudes are treated as pressure altitude. No crossover altitude between calibrated airspeed and Mach number is modelled. Any effects of varying atmospheric conditions on crossover behaviour are therefore neglected.
6) Wind and atmospheric pressure deviations from standard conditions are not modelled in the trajectory simulations. The performance calculations assume standard atmospheric conditions, consistent with the aircraft performance model used in the simulator.
7) Aircraft mass change in the simulations follows the BADA model. Payload variations, centre of gravity effects, and detailed aircraft configuration changes are not modelled. Mass change is solely due to fuel flow modelling.
8) Flight data segments containing large data gaps, unrealistic altitude jumps, or incomplete trajectory information are excluded from the analysis. This filtering assumes that the remaining trajectories are representative of nominal operational behaviour.
9) The ACMS data are assumed to provide sufficiently accurate measurements of altitude, fuel flow, and airspeed for comparative fuel and efficiency analysis. Possible sensor measurement errors and data recording precision effects are not explicitly modelled.

Eurocontrol defines level segments as flights in level flight for over twenty seconds. LVNL regards level flight if the altitude change is within 50 ft bounds and over a distance of 2.5 NM [7]. Therefore, in this research, a segment is considered level when the level segment is maintained for at least twenty seconds, below TOD and above IAF. Additionally, a segment is considered level with a maximum vertical speed of 150 feet per minute (fpm) and a negligible altitude change with a maximum Flight Path Angle (FPA) of 1.5 degrees. TOD is detected with an FPA below -1 degrees in combination with a minimum sustained descent of ten seconds and a descent rate of minimum -300 fpm. Vertical flight inefficiency in this research is defined as these level segments. The horizontal track inefficiencies are not considered. For this research, the IAF is at FL100.

VII. RESULTS

This section presents the main results of the research. First, the fuel validation of the BlueSky simulator is discussed in Subsection VII-A. Then, the KPI results and route selection are presented in Subsection VII-B. After that, the level-off sources are identified in Subsection VII-C. Finally, the effects of modifying level-off altitude and duration are shown in Subsection VII-D.

A. Fuel Validation of BlueSky Simulator

This research depends on simulations performed in the ATM simulator BlueSky. To assess the accuracy of the simulated fuel consumption, BlueSky's fuel output is validated against fuel consumption derived from the corresponding recorded flights. In addition to this validation, the BADA 3 performance model is evaluated separately to distinguish simulator errors from those in the performance model itself. This will help understand the error margins from the simulator and the performance model individually. The results are expressed as percentage differences relative to the fuel consumption from the ACMS flight data. This metric is used to be able to compare two independent measurements of the same quantity. The validation results for the BlueSky simulations compared to the real flights are shown in Figure 6. The results for validating BADA are presented in Figure 22 presented in the Appendix G.

The results show a wide range of percentage differences. In some simulations, fuel consumption is lower than observed in recorded flights, while others indicate higher values. To identify the main contributors to these differences, additional analyses are performed across the flight phases and fuel flow at different altitudes.

The flight is divided into four main flight phases: climb, cruise, descent, and approach. However, for this analysis, in Figure 7 only the cruise and descents are shown, as these are the main focus of the research. Figures 15 and 16 show additional insights into these two phases together with a complete overview of all four flight phases in Figure 17 altogether in the Appendix D. From Figure 7, it can be seen that during the cruise phase, fuel prediction of BlueSky is more consistent and accurate than during the descent flight phase. During the descent phase, a linear increase in the total fuel difference is observed with increasing fuel consumption. Similar results but for the unconstrained flight condition are presented in Appendix H.

B. KPI Results and Route Selection

After fuel validation, the arrival routes are evaluated using the defined KPIs. These KPIs combine vertical inefficiency indicators, namely average level-off impact and delta fuel burn, with operational complexity indicators, which are traffic density, sector usage, maximum traffic density, and maximum sector occupancy. The objective of this analysis is to create insights into the arrival routes of Schiphol Airport and to identify routes with high environmental improvement potential that are feasible to implement. Therefore, the level-off impact and delta fuel burn are considered benefits, while the operational complexity indicators are considered drawbacks.

The resulting KPI scores for all analysed STAR routes are shown in Table II. The column *KPI Final* represents the overall route score used for ranking. The KPIs derived from the ACMS data include information on aircraft type. For these, a score is output that indicates the mean, standard deviation and weighted performance across the different aircraft types. The *KPI Mean* reflects the average performance across aircraft types, while the *KPI Std* indicates variability between aircraft. The *KPI Weighted* score reflects the performance across aircraft types, also taking into account the number of flights operated on the route by each aircraft type.

Routes associated with STAR RIVER obtain the highest overall scores in the KPI analysis. In the end, the HELEN route achieves the highest final score of 0.712. This route combines a high level-off impact with a large delta fuel value, which indicates high potential for fuel reduction. At the same time, traffic density and sector usage remain moderate. This means improvements could produce significant environmental benefits while remaining feasible within the current operations.

The DENUT route also performs well with a score of 0.551. It shows the highest level-off impact of all routes together with a high delta fuel value. Compared to HELEN, this route also experiences high daily traffic and a high maximum traffic density. As a result, DENUT represents a case where both high environmental potential and high operational complexity are present. Improvements here would therefore have a large impact, but should account for airspace constraints, as complexity is high.

The SUGOL routes generally show moderate KPI performance. The MOLIX route, however, scores the highest of this group. With a score of 0.600, it ranks second overall. Although its level-off impact and delta fuel values are much lower than those of the RIVER routes, the route's daily traffic, maximum density, and sector usage are also lower than those of the RIVER routes. This combination makes the MOLIX route an interesting case. It represents a route with low inefficiencies and limited operational complexity. This allows analysis of vertical performance improvements within a relatively manageable route. The remaining SUGOL routes show medium impact. For example, the TOPPA and LAMSO routes show moderate level-off impact and delta fuel, while traffic indicators are between low and relatively high. These routes reflect balanced but less extreme conditions compared to the higher ranking cases.

The ARTIP routes' scores are far apart. The NORKU route has the highest daily traffic and high sector density. On the other hand, its level-off impact and delta fuel values are only moderate. Hence, it obtains the lowest overall KPI score. The environmental improvement potential does not compensate for the operational complexity. The BLUFA route performs better in terms of score, but its fuel indicators stay below those of the HELEN and DENUT routes.

To assess the robustness of these results, a sensitivity analysis of the KPI weights was performed. For each KPI, the weight was varied between 0.05 and 0.6, while the remaining weights were redistributed proportionally according to the

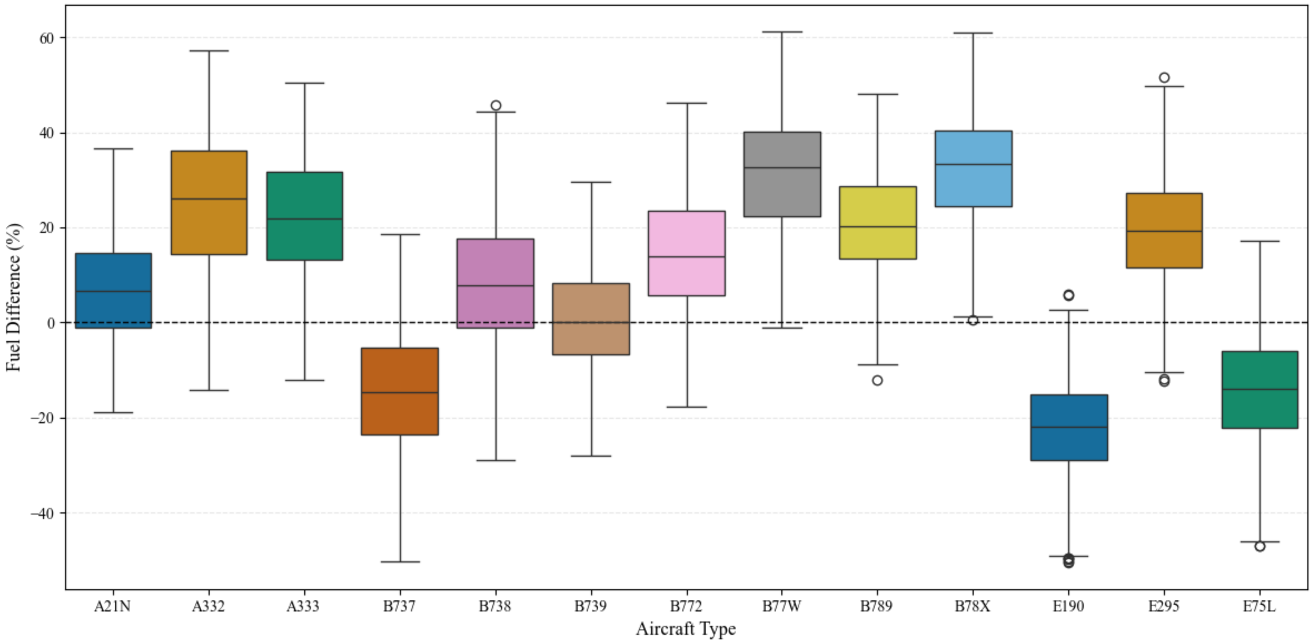


Fig. 6. Percentage Difference of Fuel Outcome from a Fixed Point before TOD until the IAF of Simulator Compared to Real Flight

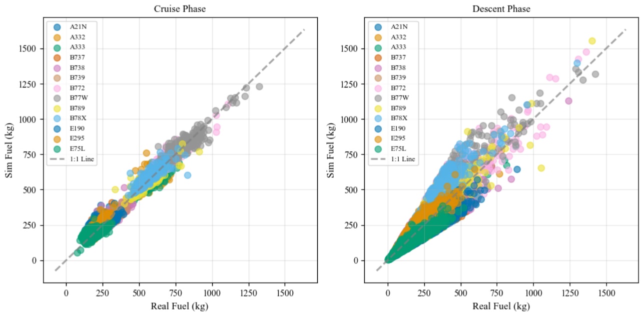


Fig. 7. Fuel Outcome Recorded Flight vs. Fuel Outcome Simulated Flight for Cruise and Descent Flight Phase

original weights. The top three routes remain within the highest-ranked positions in most cases, as shown in Figure 8. This indicates that the selection is not strongly influenced by a specific weighting distribution and that the ranking reflects differences between the routes.

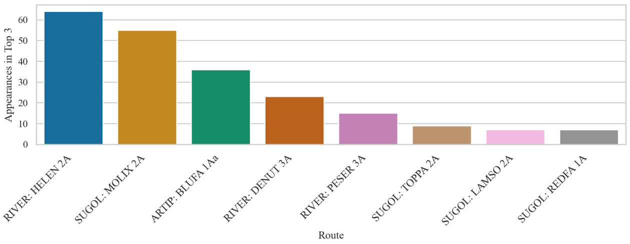


Fig. 8. Sensitivity Analysis Overview Appearance in Top Three

Figure 9 presents the radar plot of the top five routes and illustrates their KPI distribution. The HELEN route shows strong fuel-reduction potential with moderate operational complexity. DENUT combines high inefficiency with high traffic density and sector crossings. MOLIX presents moderate inefficiency under comparatively low traffic complexity. The BLUFA and TOPPA routes show more balanced KPI similar to those of the MOLIX route, with less extreme values for both fuel potential and traffic complexity.

Based on this assessment, the HELEN, DENUT, and MOLIX routes were selected for further detailed analysis. Together, these routes represent different operational contexts: one with high fuel potential and moderate complexity, one with both high fuel potential and high traffic exposure, and one with moderate inefficiency with low operational complexity. This range enables the next phase of the research to evaluate modifications to constraints under varying traffic and complexity conditions.

C. Level-off Sources

Level-off segments represent vertical inefficiencies that prevent aircraft from operating a continuous descent, resulting in a stepped descent. To identify the sources of these inefficiencies, ACMS data were analysed to determine where level-off segments most commonly occur in arrival trajectories. Level-offs were associated with specific waypoints. This enabled the identification of recurring locations.

An overview of the top ten identified level-off locations with inefficiency information is provided in Table III. Here, the number of level-offs, the altitude range, the altitude mode, the duration range, and the duration median are presented. An interesting result is that, in most cases, the altitudes match the information stated in the LoAs. Also, the restrictions presented

TABLE II
FINAL KPI RESULTS FOR ARRIVAL ROUTES

Route	Score				Key Performance Indicators					
	KPI Final	KPI Mean	KPI Std	KPI Weighted	Level-Off	Delta Fuel	Avg. Sectors	Traffic / Day	Max. Traffic Density	Max. Flights in Sector
RIVER: HELEN 2A	0.712	0.386	0.156	0.493	78.29	144.89	6.56	30.32	58	11
SUGOL: MOLIX 2A	0.600	0.271	0.040	0.279	9.65	30.57	4.81	0.32	25	4
ARTIP: BLUFA 1Aa	0.569	0.248	0.016	0.253	27.10	61.06	6.58	39.77	30	6
RIVER: DENUT 3A	0.551	0.342	0.175	0.313	88.77	145.86	7.48	137.52	129	9
SUGOL: TOPPA 2A	0.541	0.294	0.051	0.289	28.88	72.77	5.39	35.87	64	8
RIVER: PESER 3A	0.534	0.305	0.108	0.326	34.59	57.37	6.16	0.26	64	7
SUGOL: LAMSO 2A	0.534	0.209	0.057	0.219	17.51	111.81	5.53	98.90	61	9
SUGOL: REDFA 1A	0.515	0.259	0.053	0.252	25.30	84.55	5.19	78.61	51	11
ARTIP: NORKU 2A	0.253	0.111	0.037	0.111	23.08	70.77	6.47	207.71	71	16

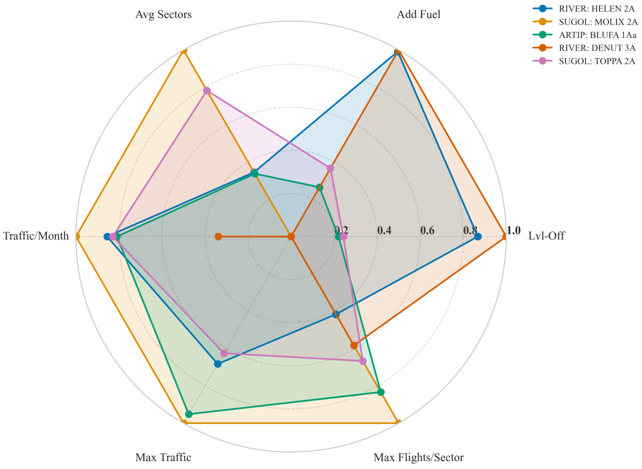


Fig. 9. Sensitivity Analysis Top Three Outcome Different KPIs

in the LoAs and RAD are sometimes higher than the actual level-off height from the recorded data. Which is the case of the waypoint DENUT, for example. For a small number of the level segments found in the data, no connection to a waypoint could be found. The level-off locations are shown in Figure 10.

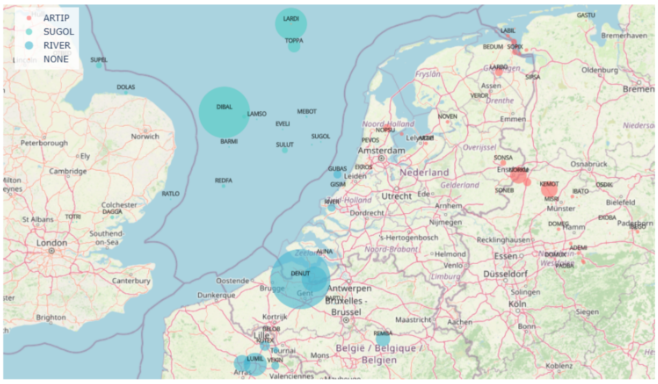


Fig. 10. Bubblemap Indicating Level-Off Location with the Size of the Bubble Indicating the Total Level-Off Duration at that Location

TABLE III
TOP 10 WAYPOINT STATISTICS FOR LEVEL-OFF SEGMENTS BELOW TOD ABOVE IAF

Waypoint	Level-Offs Count	Altitude Range (ft)	Altitude Mode (ft)	Duration Range (s)	Duration Median (s)
DENUT	28	FL200–FL250	FL200	20–240	90
DIBAL	24	FL250–FL253	FL250	20–105	39
LARDI	16	FL250–FL251	FL250	20–220	50
HELEN	12	FL150–FL250	FL150	35–455	110
LUMIL	11	FL270–FL340	FL270	40–230	105
KEMOT	8	FL260–FL330	FL260	115–205	175
NORKU	8	FL200–FL280	FL200	25–405	100
BARLI	8	FL300–FL340	FL300	30–245	102.5
REMBA	7	FL220–FL320	FL220	45–310	110
LABIL	6	FL260–FL260	FL260	80–140	110

D. Level Segment Modification Results

To evaluate the potential impact of modifying identified inefficiencies, a detailed analysis of the selected routes was performed. The selected routes are HELEN, MOLIX and DENUT. For these routes, three types of adjustments were investigated:

1) modification of level-off altitude
2) modification of level-off duration
3) a combination of altitude and duration change

The simulated results are presented for no duration change, fifteen and thirty second duration change. For each, the altitude shift results and the corresponding change in fuel consumption is presented with the uncertainty bounds shown. These results are presented in Figure 11. On average, 10-12 kg of fuel can be saved per flight with level segments by solely increasing the altitude by 2000 ft and decreasing the duration by thirty s. Complementary heat maps illustrate the general trend of fuel differences across all scenarios. These heat maps are shown in Figures 18, 19 and 20 in Appendix E.

The results show a consistent trend: reducing the level-off altitude increases fuel burn, while increasing it reduces it. Similarly, reducing the duration of level segments logically lowers fuel consumption. However, the simulated results show significant variability. To assess whether these trends are consistent with real-world behaviour, a regression analysis was performed using recorded ACMS data. Flights were grouped by similar route, aircraft type, and level-off location. Horizontal trajectories were matched to isolate flights with comparable conditions. Within these groups, differences in level-off altitude and duration were analysed against differences in fuel consumption.

Figure 12 illustrates the regression relationships for the recorded flights. Figure 13 includes bounds to separate the effects of altitude and duration to get a clearer indication of the isolated relationship. The recorded data confirm the general trends observed in simulation: higher descent profiles and shorter level segments are associated with lower fuel consumption.

The altitude isolated trend line is less accurate than the duration trend line. This makes sense because level segments along similar trajectories are mostly at similar altitudes but have different durations. Therefore, the duration effect can be more clearly distinguished from altitude, while the altitude effect is more difficult to isolate. The regression results for the combined results for recorded flights show a strong linear relationship between fuel difference indicated as ΔFuel and changes in duration, denoted by ΔD in s, and altitude, denoted by ΔA in ft:

$$\Delta\text{Fuel} = 0.5629\,\Delta\text{D} - 0.0027\,\Delta\text{A} + 0.2218 \tag{12}$$

$$R^2 = 0.818$$

For the simulated flights, the combined regression for ΔFuel with ΔD and ΔA is given by:

$$\Delta\text{Fuel} = 0.0815\,\Delta\text{D} - 0.0014\,\Delta\text{A} + 0.2092 \tag{13}$$

$$R^2 = 0.0795$$

Overall, the results indicate that incremental modifications to level-off altitude and duration can reduce fuel burn. The regression analysis confirms the directional consistency between simulated and recorded data. This also highlights the limitations of the simulation environment by capturing the high volatility across the results.

VIII. DISCUSSION

The results provide insights into three main aspects of the research: the reliability of the simulator BlueSky, the identification of vertical inefficiencies in arrival routes through KPI analysis and level-off insights, and the potential impact of modifying operational constraints. These findings are interpreted in the same order. First, the fuel validation of BlueSky is discussed in Subsection VIII-A. Then, the KPI outcomes are discussed in Subsection VIII-B. This is followed by a discussion of the level-off analysis in Subsection VIII-C and the results of the modification scenarios Subsection VIII-D. Finally, the broader implications for the implementation of CDOs are considered in Subsection VIII-E.

A. BlueSky Results and Accuracy

The validation results show a wide spread in percentage fuel differences between simulated and recorded flights, especially during the descent phase. Cruise phase predictions are relatively consistent. During the descent phase, large variability is present, and a trend of increasing error with increasing fuel burn is detected. This indicates that BlueSky does not accurately reproduce descent fuel flow behaviour.

The validation of the performance model BADA 3 shows a significantly smaller spread in fuel differences. This suggests that a large part of the observed inaccuracy originates from the simulator rather than from the BADA 3 performance model itself. Although BADA 3 performs reasonably well, it is known that BADA 3 has limitations compared to BADA 4 [36]. Therefore, integrating BADA 4 into BlueSky would likely improve fuel flow predictions.

Another source of inaccuracy is the way BlueSky models thrust and vertical navigation. In operational practice, CDOs are typically flown as idle-thrust descents or as fixed flight path angle descents guided by the aircraft's FMS. In BlueSky, however, aircraft are flown with the autothrottle permanently enabled [37]. The autothrottle continuously adjusts thrust to maintain the selected speed, regardless of the aircraft's attitude. As a result, the aircraft has limited freedom in how it executes the descent, which significantly affects descent performance.

Furthermore, although the simulator labels the descent logic as VNAV, this functionality does not fully replicate the behaviour of an aircraft FMS. Operational VNAV calculates and follows a predefined vertical trajectory, enabling aircraft to follow optimised idle-thrust descent profiles. In contrast, the BlueSky implementation approximates descent behaviour through a simplified path-following logic combined with continuous speed control via the autothrottle. This approach does not reproduce the full vertical guidance and energy management logic of an operational FMS. As a result, the simulated descents should not be interpreted as fully representative of real-world CDO behaviour.

Additionally, inspection of the log files shows unrealistic behaviour in the simulation output, such as drag values equal to zero and thrust and fuel flow initiating at zero. These characteristics do not reflect real-world aircraft operations and further explain part of the observed differences.

The regression analysis supports this interpretation. For recorded flights, the relationship between level-off duration, altitude, and fuel difference shows a strong linear fit with an R^2 of 0.818. The simulated data show high variability and a weak fit, with an $R^2 = 0.0795$. The trend direction is consistent between real and simulated data, but the simulator does not accurately capture the magnitude of the separate

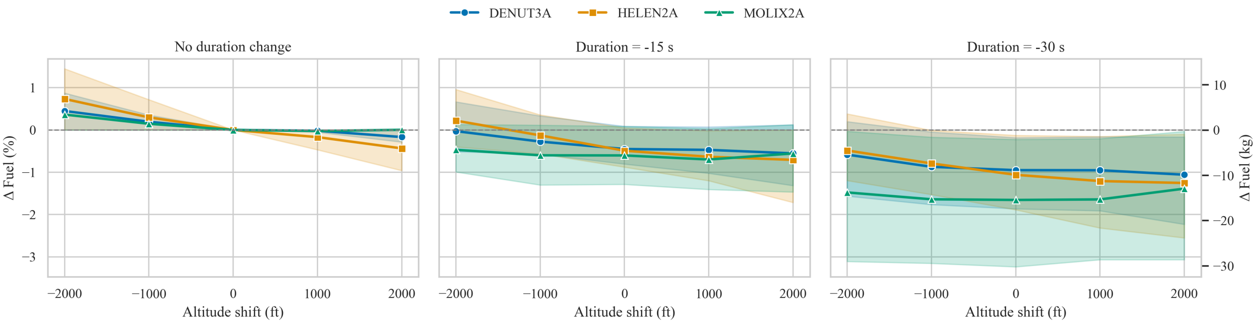


Fig. 11. Visualisation of Fuel Change in Percentage of the Flight and in Amount of kg across the Three Routes for Duration Change of Zero, Fifteen and Thirty Seconds

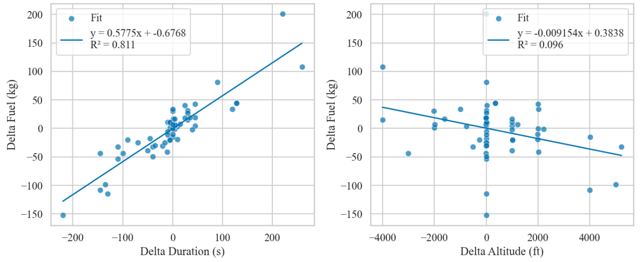


Fig. 12. Regression Lines Recorder Flight Data Comparison Flights Same Level Segment Location Different Altitude and Duration

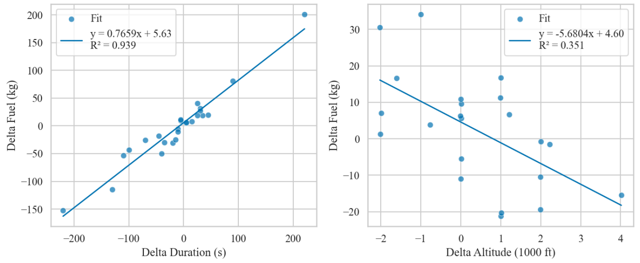


Fig. 13. Regression Lines Recorder Flight Data Comparison Flights Same Level Segment Location Different Altitude and Duration with incorporated Bounds to Isolate Effects

effects. The simulator does provide directional insight into fuel trends. However, due to this large inconsistency, the absolute fuel savings must not be interpreted as exact values, but rather as an indication of relative trends and differences between scenarios.

B. *KPI Analysis*

The KPIs were developed to combine environmental improvement potential with operational complexity. The vertical inefficiency indicators, average level-off impact and delta fuel burn represent the potential environmental benefit of modifying a route. The traffic density and sector-related indicators represent operational complexity. The KPI results show clear differences between the arrival routes. Routes associated with the RIVER STAR are the highest, indicating that they combine significant fuel reduction potential with relatively high operational complexity. In particular, the HELEN route achieves the highest overall score. Its high level-off impact and delta fuel values indicate strong environmental improvement potential, while traffic density and sector usage remain moderate. This suggests that modifying the route's constraints could provide measurable benefits without additional operational complexity.

The DENUT route also shows high environmental potential but differs in operational context. Although its level-off impact and delta fuel values are among the highest, it is also associated with high daily traffic and high maximum traffic density. This indicates that improvements on DENUT could have a large environmental impact, but implementation would require consideration of traffic and sector constraints.

The MOLIX route presents a different case. While its inefficiency indicators are lower than those of HELEN and DENUT, its operational complexity indicators are also relatively low. This results in a high overall ranking. MOLIX therefore represents a route where improvements may be easier to implement, even if the absolute fuel savings are smaller.

The ARTIP routes are diverse results. The NORKU route has high traffic exposure and sector density but only moderate vertical inefficiencies, resulting in a low overall score. Here, operational complexity weighs more than the environmental benefit. The BLUFA route performs better but does not achieve the fuel savings potential of the higher-ranking RIVER routes.

Selecting HELEN, DENUT, and MOLIX for further analysis ensures that subsequent constraint modifications are evaluated under different operational conditions. This supports the objective of assessing both environmental benefit and implementation feasibility.

Horizontal trajectories were matched to isolate comparable flights. However, variations in traffic distribution, seasonal effects, and meteorological conditions across the analysed month limit direct comparability between routes.

C. *Level-off Analysis*

The level-off analysis was performed to identify the sources of vertical inefficiencies within the arrival routes. The analysis shows a strong relationship between vertical inefficiencies and waypoint restrictions defined in LoAs and the RAD. Most level-off segments occur at altitudes that closely match these constraints. For example, for waypoint-restrictions at DIBAL, LARDI, and NORKU, the level-off altitude mode matches the altitude level allocation stated in the LoA. In several cases, such as DENUT, the recorded level-off altitude is slightly below the known restriction, indicating some deviations around the constrained altitude while still adhering to the operational requirement.

These findings indicate that most observed level segments are procedure-driven rather than caused by deviations from optimal flight profiles. Aircraft generally follow the altitude restrictions defined in operational procedures, which results in temporary level segments when the aircraft reaches a constrained altitude before the next descent segment can begin. Consequently, the observed vertical inefficiencies are driven by the design of the arrival procedures themselves. Also, the level segment observations lower than the set altitude restrictions indicate that small targeted adjustments in level segment altitude are possible, and savings can be realised.

Identifying the exact origin of individual constraints is not always straightforward. Various altitude restrictions originate from LoAs between ANSPs, which are not publicly available, while others are defined in the RAD and published. In addition, several analysed arrival routes begin their descent outside the Dutch FIR. As a result, parts of the descent profile and associated level-off segments are within operational constraints defined by neighbouring ANSPs. Because LoAs are not publicly available and operational information is distributed across different organisations, identifying the exact source of some constraints requires interpretation of multiple documentation sources, which are often hard to come by.

D. Level Segment Modification Results

The modification scenarios demonstrate that incremental adjustments to level-off altitude and duration affect fuel consumption. Increasing the altitude at which a level segment occurs reduces fuel burn, whereas maintaining a lower level-off altitude increases fuel consumption. In addition, reducing the duration of level segments decreases fuel consumption. Even small changes, such as a five-second reduction in duration, produce measurable differences.

The regression analysis using recorded flight data confirms this trend. For recorded flights, level-off duration and altitude explain a large proportion of the variation in fuel differences, as reflected by the high R^2 value. This indicates that vertical inefficiencies in real operations are strongly linked to these two parameters. In contrast, the simulated data show greater variability and lower explanatory power. This reflects limitations in the simulator's modelling of descent behaviour. However, the trend direction is consistent between the recorded and simulated data. This supports the conclusion that incremental adjustments can reduce fuel burn without requiring structural redesign of the airspace.

Nevertheless, the operational feasibility of such adjustments must be considered. Many altitude restrictions are introduced to ensure safe separation between traffic flows, to facilitate sector coordination, or to support arrival sequencing in the terminal area. Modifying these constraints can therefore introduce additional operational complexity or increase controller workload. Furthermore, several constraints originate from LoAs between different ANSPs, meaning that any changes would require coordination between multiple organisations.

In addition, the simulations used in this study analyse individual flights and therefore do not account for traffic interactions or conflict detection and resolution. In real-world operations, traffic density, weather conditions, and airport configuration may influence whether modified descent profiles can be applied consistently. The total environmental benefit therefore depends not only on the fuel savings achieved per flight, but also on the proportion of flights that are able to apply the modified procedures under operational conditions.

E. Implementation of CDOs

The results indicate that improvements in vertical efficiency do not necessarily require a full redesign of the airspace. Incremental adjustments to existing constraints can already produce measurable fuel savings. These adjustments can be evaluated and implemented per route. Airspace redesign has been proposed in previous research, but such changes are complex and time-consuming. Other concepts, such as Free Route Airspace (FRA), aim to reduce lateral constraints and sector-based routing limitations [38]. FRA can reduce reliance on fixed handover points and predefined routes. However, FRA primarily focuses on horizontal routing flexibility and does not automatically resolve vertical inefficiencies caused by altitude restrictions. Therefore, while FRA may support more efficient trajectory management, the vertical constraints identified in this research require review separate from lateral airspace design.

The results show that improvements can be achieved without altering route structures or sector boundaries. By adjusting specific altitude constraints or reducing the duration of level segments, vertical efficiency can be improved within the existing airspace configuration. However, implications for sector capacity should still be taken into account and further researched. Also, the total environmental benefit depends not only on per-flight fuel savings but also on traffic volume. Routes with high traffic density offer greater cumulative fuel reduction potential. Therefore, prioritising high-impact routes can maximise overall benefit while limiting operational disruption.

Implementing CDO procedures requires coordinated action among ATS units. Most of the identified inefficiencies originate from altitude restrictions defined in LoAs and procedures. Therefore, targeted constraint reviews and small procedural changes can support the gradual implementation of CDOs in constrained airspaces.

An additional challenge in this research is the availability of operational information across FIRs. For many of the analysed arrival routes, the TOD occurs outside the Dutch FIR. Identifying the origin of specific constraints requires significant effort and coordination with multiple stakeholders. Improving the transparency and accessibility of operational constraints across various FIRs would support both operational optimisation and research. Increased data sharing and more accessible documentation of trajectory constraints could support more integrated trajectory analysis, essential for concepts such as TBO and CDO.

IX. FUTURE WORK

This research identifies several areas that require further investigation to support the results and to ensure operational implementation. The following aspects outline potential areas for further research of this study.

First, the current simulations do not incorporate conflict detection and resolution. All flights are modelled as independent trajectories with no interactions. In actual flight operations, separation and sequencing constraints significantly affect descent profiles. Future research should integrate conflict detection and resolution to evaluate whether the proposed changes are feasible in more realistic operational contexts. Additional performance indicators, such as loss of separation counts or the number of conflict resolution interventions during CDOs, could be included.

Second, the influence of surrounding traffic should also be considered in more detail. Operational priorities, such as clearing departing traffic efficiently through Continuous Climb Operations (CCO), may affect descent flexibility for arriving aircraft. Future research could analyse how arrival and departure flows influence the feasibility of CDO implementation.

Next, the simulations rely on the BADA performance model as implemented in BlueSky. Although it was validated as useful for comparative analysis, alternative performance models, such as the iLabs model available in BlueSky, can provide a different representation of aircraft behaviour due to their different implementations in BlueSky. Future work should compare performance models and their implementation within the simulator and validate their fuel and descent predictions against recorded flight data. This would improve confidence in the absolute magnitude of the quantified fuel savings.

Sector usage and controller workload are not explicitly modeled in this study. In operational settings, descent constraints are closely associated with sector capacity and workload management. Extending the analysis to incorporate dynamic sector configurations and workload indicators could provide insights into the relationship between vertical inefficiencies and operational capacity constraints. This approach would support the evaluation of trade-offs between environmental performance and controller workload.

In addition, the justification of existing constraints requires further examination. Some restrictions are implemented for safety, while others can originate from outdated procedures. Assessing the reasons for these constraints could clarify which restrictions are essential and which could be revised, with modern improvements in navigation, surveillance, and communication technologies. Further research could also analyse how to integrate improved environmental performance into airspace design, and how to balance fuel efficiency with safety and capacity requirements during procedure development.

While this study focuses on Schiphol arrivals, applying the methodology to other airports would enable comparisons of inefficiencies across different operational environments. Access to more detailed and non-anonymised operational data would aid the validation of the model and the analysis of aircraft intent, meteorological conditions, and controller interventions. This would reduce uncertainty in fuel estimation and support the assessment of the feasibility of operational implementation.

Finally, the current findings depend on simulation for each flight trajectory modification separately. Future research should aim to develop a simplified analytical framework to estimate the fuel and emissions impacts of constraint modifications without the need for the full trajectory simulation. This framework would make it easier to evaluate procedures and changes to constraints, for example, in airspace design studies.

X. CONCLUSIONS

ATS fulfil an important role in reducing fuel burn and emissions. To contribute to this goal, a direct operational improvement is to enable aircraft to fly more continuous descents. However, in practice, aircraft are still constrained by altitude restrictions, sector boundaries, and agreements between ATS units. Therefore, this research investigated vertical descent inefficiencies in arrivals, using Schiphol Airport as a case study. The research evaluated how incremental modifications to existing constraints could improve descent performance. A total of more than 8000 recorded flights from ACMS data and one month of DDR traffic data were analysed.

The results show a clear relationship between observed level-off segments and altitude restrictions defined in LoAs and the RAD. Therefore, most vertical inefficiencies result from current airspace constraints. The simulated adjusted scenarios results and the regression analysis of recorded flights both show that longer level-off duration and lower level-off altitude are associated with increased fuel consumption. Both show that increasing altitude constraints or reducing level-off duration leads to lower fuel burn. For the analysed scenarios, increasing the level-off altitude by up to 2000 ft and reducing the level-off duration by 30 s resulted in fuel savings of approximately 10–12 kg per flight with level segments. This shows that incremental changes to operational constraints can already produce measurable improvements.

The fuel consumption for the various flights was estimated using the BlueSky simulator and validated against recorded flight data. The validation shows that BlueSky is not sufficiently accurate in modelling descent fuel flow and vertical trajectory behaviour. However, simulated fuel savings should therefore be interpreted as an indication rather than an exact value. Although these limitations are present, the general trends identified in this research are considered valid. The results show that meaningful fuel savings can be achieved without full airspace redesign, simply by adjusting existing altitude constraints where operationally feasible.

The implementation of these adjustments is challenged by coordinating among different ATS providers. Modifying altitude restrictions requires alignment between ANSPs and agreement on traffic management priorities. Improved collaborative decision-making and agreements would support the gradual implementation of more efficient descent operations.

This research is limited by the data being provided in anonymised form. As a result, flight-specific conditions such as weather or ATC instructions could not be analysed. Other contributors to inefficiency, such as changes in horizontal routing, were not investigated. Horizontal airspace redesign and concepts such as FRA can further reduce inefficiencies, but were outside the scope of this thesis.

In conclusion, this thesis shows that vertical inefficiencies in Schiphol arrival operations are largely procedure-driven and that incremental adjustments to constraints can already produce measurable fuel savings. The research provides an effective framework for quantifying the fuel consumption of specific restriction changes and can serve as a base for further detailed analysis of airspace optimisation and the implementation of CDOs.

REFERENCES

[1] CORSIA. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). [Online]. Available: https://www.icao.int/CORSIA

[2] D. Xue, S. Du, B. Wang, W.-L. Shang, N. Avogadro, and W. Y. Ochieng, "Low-carbon benefits of aircraft adopting continuous descent operations," vol. 383, p. 125390. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261925001205

[3] IATA. Our Commitment to Fly Net Zero by 2050. [Online]. Available: https://www.iata.org/en/programs/sustainability/flynetzero/

[4] EUROCONTROL. Continuous climb and descent operations (CCO / CDO) — EUROCONTROL. [Online]. Available: https://www.eurocontrol.int/concept/continuous-climb-and-descent-operations

[5] R. Dalmau, J. Sun, and X. Prats, "Fuel Inefficiency Characterisation and Assessment due to Early Execution of Top of Descents." [Online]. Available: https://repository.tudelft.nl/record/uuid:6fbc7611-51a6-4508-add7-b3aeec390813

[6] K. A. ter Beek, "High capacity Continuous Descent Operations." [Online]. Available: https://repository.tudelft.nl/record/uuid:7c57298e-23e9-408b-98a4-dbb2c63ed7ad

[7] LVNL. eAIS Package for NETHERLANDS. [Online]. Available: https://eaip.lvnl.nl/web/2025-07-24-AIRAC/html/index-en-GB.html

[8] X. Olive, J. Sun, L. Basora, and E. Spinielli, "Environmental inefficiencies for arrival flights at European airports," vol. 18, no. 6, p. e0287612. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0287612

[9] J. Fiala, T. Pilmannová, and S. Schmidt, "Impact of continuous climb/descent procedure implementation on ATCO workload," in *2024 New Trends in Aviation Development (NTAD)*, pp. 32–37. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10850352

[10] S. Da Silva, "Continuous Descent Operations (CDO)."

[11] T. Reynolds, "Analysis of Lateral Flight Inefficiency in Global Air Traffic Management," in *The 26th Congress of ICAS and 8th AIAA ATIO*. American Institute of Aeronautics and Astronautics. [Online]. Available: https://arc.aiaa.org/doi/10.2514/6.2008-8865

[12] ICAO. Pbn Overview. Pbn Overview. [Online]. Available: https://www.icao.int/safety/pbn/pbn-overview

[13] SKYbrary. Performance Based Navigation (PBN) — SKYbrary Aviation Safety. [Online]. Available: https://skybrary.aero/articles/performance-based-navigation-pbn

[14] ICAO, "PERFORMANCE-BASED NAVIGATION MANUAL," ICAO.

[15] C. Borst. Communication, Navigation & Surveillance: Lecture slides - AE4302 Avionics and Operations (2024/25 Q2). [Online]. Available: https://brightspace.tudelft.nl/d2l/le/content/679230/viewContent/3739621/View

[16] LVNL. Mode s enhanced surveillance: Lost miscommunicatie op. LVNL. [Online]. Available: https://www.lvnl.nl/veiligheid/veiligheidssystemen/mode-s-enhanced-surveillance-lost-miscommunicatie-op

[17] Secondary Surveillance Radar (SSR) — SKYbrary Aviation Safety. [Online]. Available: https://skybrary.aero/articles/secondary-surveillance-radar-ssr

[18] T. Scheffers, "Effects of increased trajectory predictability by ATS datalink on ATM operations in lower airspace." [Online]. Available: https://repository.tudelft.nl/record/uuid:3cfc75fe-478e-4a1c-a0c1-b5c9376bd298

[19] ICAO, *ANNEX 11 (2018): Air Traffic Services*. ICAO.

[20] T. Verboon, "Applications of ADS-C."

[21] J. Jaekel, G. Hirte, and H.-M. Niemeier, "Air traffic control and vertical approach efficiency at the lower airspace," vol. 16, no. 2, pp. 591–611. [Online]. Available: https://doi.org/10.1007/s13272-024-00805-y

[22] T. J. Mulder. Flight Management System: Lecture slides - AE4302 Avionics and Operations (2024/25 Q2). [Online]. Available: https://brightspace.tudelft.nl/d2l/le/content/679230/viewContent/3739622/View

[23] N. E.-D. Safwat, K. Thangavel, and R. Sabatini, "Challenges and Opportunities in Communication Systems for Multi-Domain Air Traffic Management," in *2025 AIAA DATC/IEEE 44th Digital Avionics Systems Conference (DASC)*, pp. 1–9. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/11257258

[24] E. Aydoğan, S. Özmen, F. A. Cetek, R. M. A. Valdés, R. D.-A. Jurado, A. E. C. Fernández, A. M. Miralles, T. Vendruscolo, S. Bonelli, D. Delahaye, S. Chaimatanan, F. Chen, and R. Hamzaoui, "Air Traffic Management and Communication over ATN/IPS for Future Datalink Communication," in *2025 Integrated Communications, Navigation and Surveillance Conference (ICNS)*, pp. 1–10. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10976836

[25] T. J. Mulder and C. Borst. Future Air Navigation System: Lecture slides - AE4302 Avionics and Operations (2024/25 Q2). [Online]. Available: https://brightspace.tudelft.nl/d2l/le/content/679230/viewContent/3739663/View

[26] G. A. D. Meo, C. Montrucchio, and G. Medici, "INTEROPERABILITY OF MILITARY AIRCRAFT VERSUS FUTURE AIR NAVIGATION SYSTEM (FANS)."

[27] EUROCONTROL. European Continuous Climb and Descent Operations Action Plan — EUROCONTROL. [Online]. Available: https://www.eurocontrol.int/publication/european-cco-cdo-action-plan

[28] ——, "Annex A - CCO/CDO Facilitation and Execution."

[29] J. Ellerbroek, M. Inaad, and J. M. Hoekstra, "Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol."

[30] H. Aksoy, O. Usanmaz, and E. T. Turgut, "Effect of vertical profile inefficiency during descent on fuel burn, emissions and flight time," vol. 122, no. 1252, pp. 913–932. [Online]. Available: https://www.cambridge.org/core/journals/aeronautical-journal/article/abs/effect-of-vertical-profile-inefficiency-during-descent-on-fuel-burn-emissions-and-fligh
5FE3F0AF15D6511DEE5AF62B656D9D98

[31] MUAC, "Continuous Descent Operations (CDO) - EDDF DIXAT ARR."

[32] EUROCONTROL. User Manual for the Base of Aircraft Data (BADA) — EUROCONTROL. [Online]. Available: https://www.eurocontrol.int/publication/user-manual-base-aircraft-data-bada

[33] J. M. Hoekstra and J. Ellerbroek, "BlueSky ATC Simulator Project: An Open Data and Open Source Approach."

[34] EUROCONTROL, "DDR Reference Manual."

[35] ICAO. KPI OVERVIEW - ICAO GANP Portal. GANP Portal. [Online]. Available: https://www4.icao.int/ganpportal/ASBU/KPI

[36] D. Poles, A. Nuic, and V. Mouillet, "Advanced aircraft performance modeling for ATM: Analysis of BADA model capabilities," in *29th Digital Avionics Systems Conference*. IEEE, pp. 1.D.1–1–1.D.1–14. [Online]. Available: http://ieeexplore.ieee.org/document/5655518/

[37] F. C. Schornagel, "Improving climb and descent profiles in BlueSky using ATC performance models."

[38] J. Dekker, "Introducing Free airspace, a way to solve Europe's airspace capacity issues." vol. 56, pp. 19–28. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S235214652100630X

APPENDIX A
SCENARIO FILE

A scenario file is a BlueSky input to generate scenarios. A scenario can include many aircraft, but increasing this number will make the run take longer. The scenarios can include many commands, which are documented on the Wiki: https://github.com/TUDelft-CNS-ATM/bluesky/wiki. The commands used here are:

- TAXI OFF: switches off ground mode
- CRELOG: creates a log with the name 'X', but needs to add parameters to file 'X' through 'X' add id, type, mass, etc, and turn on the log creator through the command 'X' on
- PERF: indicates the performance model to be used for the simulation

- CRE: initiates the creation of an aircraft by aircraft identification, type, location, heading, altitude and speed
- ADDWPT: creates a waypoint for an aircraft with latitude, longitude, altitude, and speed
- WIND: adds wind for an aircraft at a certain latitude, longitude, with a certain direction and speed
- DEST: adds a destination to the aircraft
- LNAV: turns on lateral navigation
- VNAV: turns on vertical navigation
- FF: fast forwards the whole scenario during simulation

A standard scenario file can look like Listing 1:

Listing 1. Scenario file example

```
00:00:00 > TAXI OFF 50

00:00:00 > CRELOG B737_part01 0.5
00:00:00 > B737_part01 add id, type, lat, lon,
     alt, gs, tas, vs, cas, M, hdg, trk, perf.
    fuelflow, perf.mass, perf.thrust, perf.
    drag
00:00:00 > B737_part01 on

00:00:04 > PERF bada

00:00:05 > CRE B73-001 B737 52.463 8.680 275.5
     FL360 261
00:00:05 > ADDWPT B73-001, 52.464 8.666, FL360
    , 262
00:00:05 > WIND 52.464, 8.666, 290.0, 79.0
00:00:05 > ADDWPT B73-001, 52.464 8.652, FL360
    , 261
00:00:05 > WIND 52.464, 8.652, 290.1, 78.6

...

00:00:05 > DEST B73-001 EHAM
00:00:05 > B73-001 LNAV ON
00:00:05 > B73-001 VNAV ON

00:00:06 > FF
```

Appendix B
Batch File

Scenarios are run in batches to speed up the simulations. To run a batch in BlueSky, scenarios are created normally as presented in Appendix A. Batch scenarios are run in BlueSky using the BATCH command in the command line, followed by the batch_file.scn. These scenario files are then written in a batch file as presented in Listing 2:

Listing 2. Batch file calling individual B737 scenario files

```
00:00:00.00 > SCEN B737_part01
00:00:00.00 > PCALL B737_part01.scn
04:00:00.00 > HOLD

00:00:00.00 > SCEN B737_part02
00:00:00.00 > PCALL B737_part02.scn
04:00:00.00 > HOLD

00:00:00.00 > SCEN B737_part03
00:00:00.00 > PCALL B737_part03.scn
04:00:00.00 > HOLD

00:00:00.00 > SCEN B737_part04
00:00:00.00 > PCALL B737_part04.scn
04:00:00.00 > HOLD

00:00:00.00 > SCEN B737_part05
00:00:00.00 > PCALL B737_part05.scn
04:00:00.00 > HOLD

00:00:00.00 > SCEN B737_part06
00:00:00.00 > PCALL B737_part06.scn
04:00:00.00 > HOLD
```

Appendix C
Level-Off Analysis

Figure 14 shows the level-off count and average duration for the different routes during the times of the day. This additional plot provides insight into the reason for the KPI level-off impact. As can be seen, a low level-off count does not necessarily coincide with a low level-off duration.

Appendix D
Fuel Validation BlueSky

Figure 15 clearly shows the fuel error of the cruise phase compared to the descent phase for the different aircraft types.

Figure 16 shows the mean fuel error with the error margins.

Figure 17 shows the mean error of the four phases: climb, cruise, descent and approach.

Appendix E
Adjusted Scenarios

Figures 18, 19 and 20 are heatmaps presenting the results per investigated route.A general trend in duration and altitude change is evident.

Appendix F
Dashboard Analysis

The dashboard is used for in depth analysis of the recorded flight data. Flights can be selected and reviewed on various parameters such as TOD, level segments,sector usage and waypoint crossings. A quick overview of how the dashboard looks is provided in Fig. 21.

Appendix G
BADA Validation

Figure 22 shows the validation of the performance model BADA 3.16. It is clear that BADA can be used as an accurate method for estimating fuel flow in flights.

Appendix H
Unconstrained Flight Simulations and Validation

Next to the in-depth analysis of the causes of inconsistent fuel flow measurements of the simulator, unconstrained scenarios need to be validated as well. A list of unconstrained flights generated from the ACMS data was compared with unconstrained flights on the same or similar routes. The outcome of this analysis is presented in Figure 23.

The unconstrained simulations show significantly lower fuel consumption, primarily due to an extended cruise phase

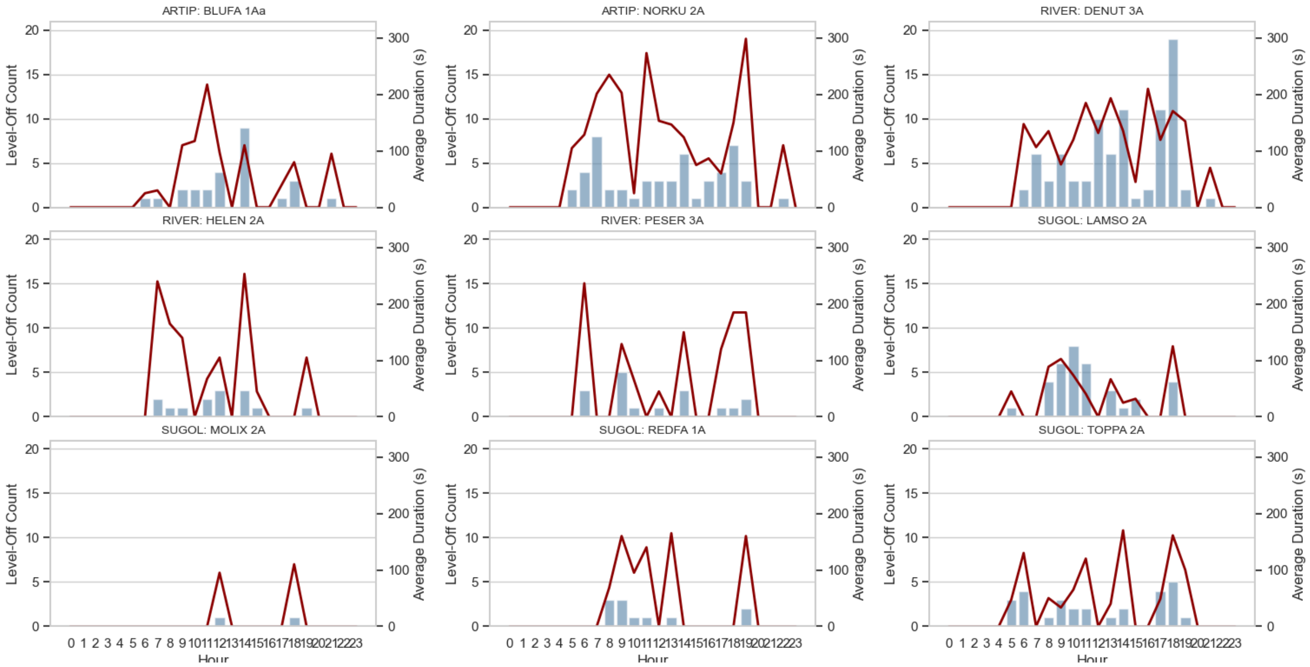


Fig. 14. Level-Off Count Depicted as the Bars and Average Duration Depicted as the Lines for the Different Routes at Different Times a Day

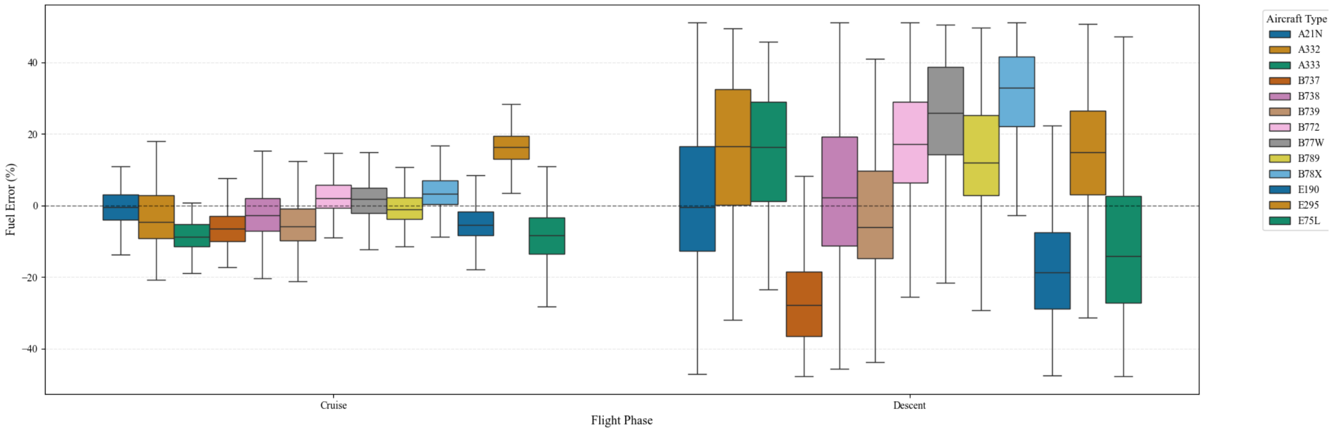


Fig. 15. Fuel Difference of Fuel Outcome Simulated Flight and Recorded Flights for Cruise and Descend Flight Phase

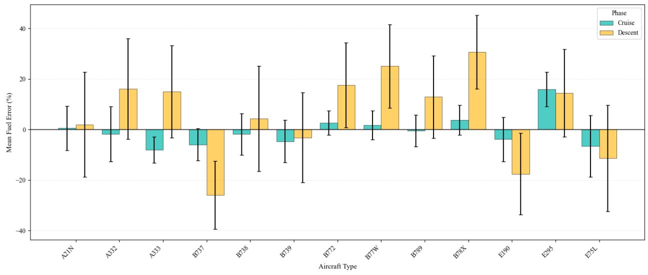
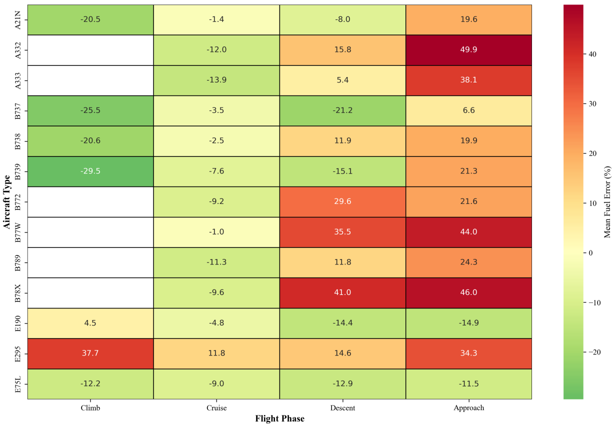


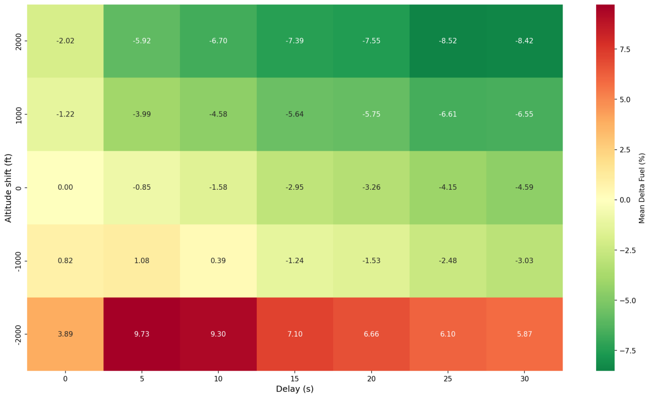
Fig. 16. Mean Fuel Error Fuel Outcome Simulated Flight compared to Recorded Flight for Cruise and Descend Flight Phase

and uninterrupted descent. This represents the theoretical maximum improvement potential, but the magnitude of this reduction must be interpreted with caution because of the known inconsistencies in the simulation environment. Therefore, comparison with recorded flight data is important to assess realistic improvement ranges.



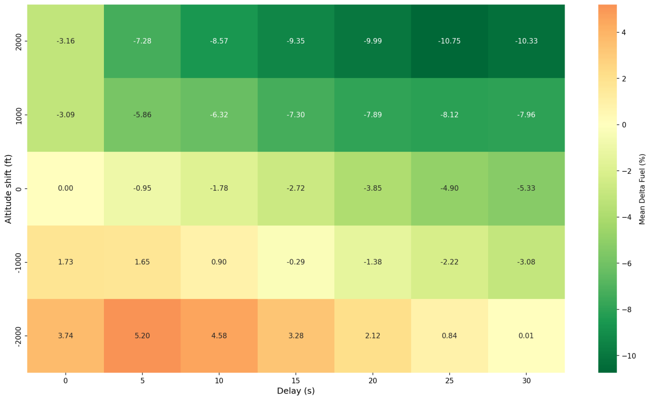
Aircraft Type	Climb	Cruise	Descent	Approach
A21N	-20.5	-1.4	-8.0	19.6
A332		-12.0	15.8	49.9
A333		-13.9	5.4	38.1
B737	-25.5	-3.5	-21.2	6.6
B738	-20.6	-2.5	11.9	19.9
B739	-29.5	-7.6	-15.1	21.3
B772		-9.2	29.6	21.6
B77W		-1.0	35.5	44.0
B789		-11.3	11.8	24.3
B78X		-9.6	41.0	46.0
E190	4.5	-4.8	-14.4	-14.9
E295	37.7	11.8	14.6	34.3
E75L	-12.2	-9.0	-12.9	-11.5

Fig. 17. Fuel Mean Error Heatmap Showing Four Phases of the Flights



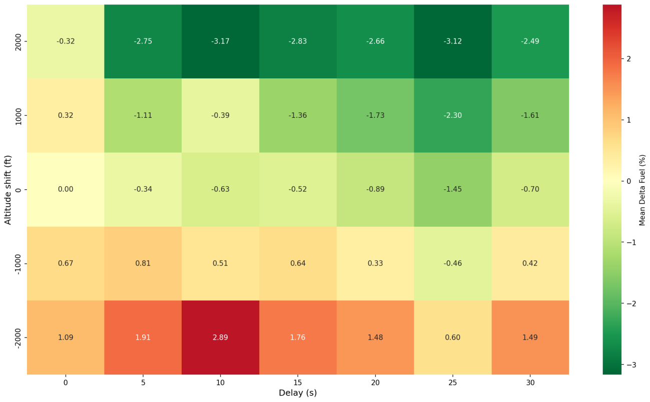
Altitude shift (ft)	0	5	10	15	20	25	30
2000	-2.02	-5.92	-6.70	-7.39	-7.55	-8.52	-8.42
1000	-1.22	-3.99	-4.58	-5.64	-5.75	-6.61	-6.55
0	0.00	-0.85	-1.58	-2.95	-3.26	-4.15	-4.59
-1000	0.82	1.08	0.39	-1.24	-1.53	-2.48	-3.03
-2000	3.89	9.73	9.30	7.10	6.66	6.10	5.87

Fig. 18. Heatmap Route DENUT 3A



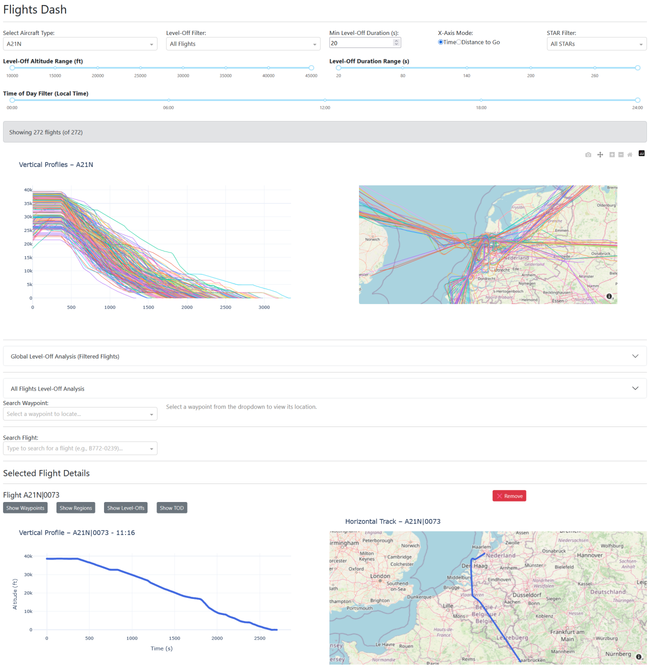
Altitude shift (ft)	0	5	10	15	20	25	30
2000	-3.16	-7.28	-8.57	-9.35	-9.99	-10.75	-10.33
1000	-3.09	-5.86	-6.32	-7.30	-7.89	-8.12	-7.96
0	0.00	-0.95	-1.78	-2.72	-3.85	-4.90	-5.33
-1000	1.73	1.65	0.90	-0.29	-1.38	-2.22	-3.08
-2000	3.74	5.20	4.58	3.28	2.12	0.84	0.01

Fig. 19. Heatmap Route HELEN 2A



Altitude shift (ft)	0	5	10	15	20	25	30
2000	-0.32	-2.75	-3.17	-2.83	-2.66	-3.12	-2.49
1000	0.32	-1.11	-0.39	-1.36	-1.73	-2.30	-1.61
0	0.00	-0.34	-0.63	-0.52	-0.89	-1.45	-0.70
-1000	0.67	0.81	0.51	0.64	0.33	-0.46	0.42
-2000	1.09	1.91	2.89	1.76	1.48	0.60	1.49

Fig. 20. Heatmap Route MOLIX 2A



Flights Dash

Select Aircraft Type: A21N

Level-Off Filter: All Flights

Min Level-Off Duration (s): 20

X-Axis Mode: ● Time ○ Distance to Go

STAR Filter: All STARs

Level-Off Altitude Range (ft)

Level-Off Duration Range (s)

Time of Day Filter (Local Time)

Showing 272 flights (of 272)

Vertical Profiles – A21N

Global Level-Off Analysis (Filtered Flights)

All Flights Level-Off Analysis

Search Waypoint: Select a waypoint to locate...

Select a waypoint from the dropdown to view its location.

Search Flight: Type to search for a flight (e.g., B772-0239)...

Selected Flight Details

Flight A21N|0073

Vertical Profile – A21N|0073 - 11:16

Horizontal Track – A21N|0073

Fig. 21. Dashboard Recorder Flight Data Analysis

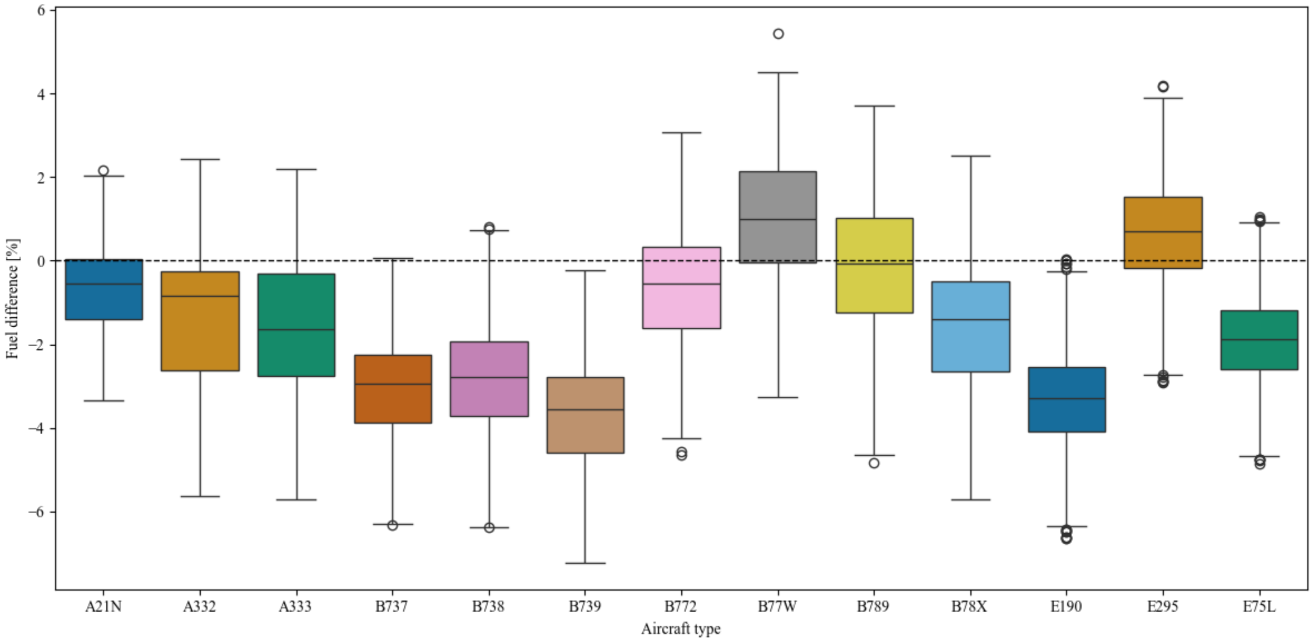


Fig. 22. Percentage Difference of Fuel Outcome for Total Flight of BADA3 Data Compared to the Real Flight

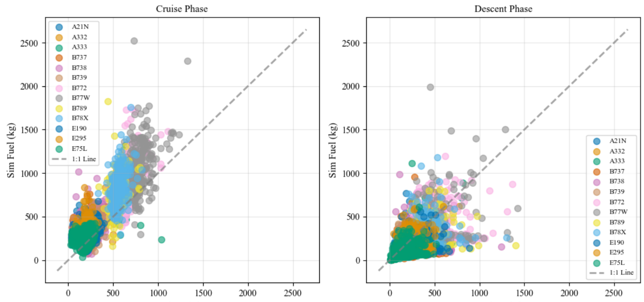


Fig. 23. Fuel Outcome Recorded Flight vs. Fuel Outcome Simulated Flight for Unconstrained Flights for Cruise and Descent Flight Phase

Part II

Literature Review

Nomenclature

Abbreviations

Abbreviation	Definition
3DE	3-Degree Efficiency
4D	4 Dimensional
ACC	Area Control Center
ACMS	Aircraft Condition Monitoring System
ADS-B	Automatic Dependent Surveillance–Broadcast
AIP	Aeronautical Information Products
ANSP	Air Navigation Service Provider
APP	Approach/Departure
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
BADA	Base of Aircraft Data
BFFM2	Boeing Fuel Flow Method 2
CCO	Continuous Climb Operation
CDA	Continuous Descent Approaches
CDO	Continuous Descent Operation
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CTA	Control Zone
CTR	Control Area
EGLL	Heathrow Airport
EHAM	Amsterdam Schiphol Airport
EU	European Union
FAB	Functional Airspace Block
FAF	Final Approach Fix
FDR	Flight Data Recorder
FIR	Flight Information Region
FL	Flight Level
FMS	Flight Management System
FPA	Flight Path Angle
FRA	Free-Route Airspace
GFS	Global Forecasting System
GPS	Global Positioning System
IATA	International Air Transport Association
LVNL	Luchtverkeersleiding Nederland
MUAC	Maastrict Upper Area Control
PBN	Performance-Based Navigation

Abbreviation	Definition
PEP	Performance Engineering Program
PM	Particulate Matter
PMS	Point Merge System
QAR	Quick Access Recorder
RNAV	Area Navigation
RNP	Required Navigation Performance
ROD	Rate of Descent
SAF	Sustainable Aviation Fuel
SES	Single European Sky
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TBO	Trajectory-Based Operation
TEM	Total Energy Model
TMA	Terminal Maneouvring Area
TOD	Top of Descent
TSFC	Thrust-Specific Fuel Consumption
TWR	Tower
UTA	Upper Control
VFI	Vertical Flight Inefficiency

2

Introduction

The aviation industry contributes significantly to global greenhouse gas emissions, and its environmental impact is expected to grow as air traffic continues to increase. To decrease or limit the environmental impact, initiatives like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aim for carbon-neutral growth in international aviation through making airlines adopt more fuel-efficient operations and invest in carbon reduction projects [2]. Also, the International Air Transport Association (IATA) goal is to achieve net-zero emissions by 2050, with a 45 % reduction targeted by 2030 [3]. To achieve these targets, improvements across multiple areas, including aircraft technology, alternative fuels, and operational efficiency, are needed. This research focuses on the last part: making current flight operations more efficient.

One of the main areas where inefficiencies occur is during the descent phase of flight. Due to fixed routes, procedural constraints, and airspace restrictions, aircraft often can't fly their optimal vertical profiles. This leads to stepped descents. These extra level-offs cause unnecessary fuel burn and CO_2 emissions. By improving how aircraft can manage their descent through concepts like Trajectory-Based Operations (TBO) and Continuous Descent Operations (CDOs), the possibility of reducing these inefficiencies increases. However, the airspace structure still limits how much benefit can be achieved. This thesis will investigate how specific restrictions in the Dutch airspace affect the vertical profiles of aircraft and how these restrictions translate into environmental benefits. The goal is to analyse these inefficiencies in detail and quantify them in terms of fuel consumption and CO_2 emissions. The research will approach this step-by-step, examining how small procedural changes can already have an impact and what is needed to make those changes possible within the TBO framework and CDOs. The project will also focus on identifying where these inefficiencies are most significant and which regions in the Dutch airspace are most affected. In essence, this research aims to identify the sources of fuel inefficiencies in current descent operations and investigate how TBO, applied incrementally, can improve these issues.

The document is set up in the following way: first, the problem is established in Chapter 3. Then, in Chapter 4, the background information is presented. In Chapter 7, the state of the art, an overview of the papers read, and an overview of the different approaches are presented. Then, in Chapter 5, the gaps in research of previous studies are stated, and the limitations that are present. Lastly, the research objective, including the methodology used, is phrased in Chapter 6.

3

Problem Definition

This chapter outlines the problem addressed in this thesis and the motivation behind the project. The focus lies on what inefficiencies and restrictions are, and what the problem is that is being solved. First, the reason why this project was created is stated in Section 3.1. Then, the inefficiencies together with the current restrictions in the Dutch airspace are discussed in Section 3.2 and Section 3.3. Lastly, the main problem to be solved during this thesis is phrased in Section 3.4.

3.1. Motivation

The air traffic industry is experiencing steady growth because of the increasing demand for global connectivity and the expansion of international trade [4]. Even though aviation has an important role in connectivity, it contributes significantly to global greenhouse gas emissions with over 2 % contribution to the global CO_2 emissions [2, 5]. Therefore, positively contributing to this growing industry is critical as this will make a lasting impact on the environment.

Various initiatives are already working on making aviation more sustainable. According to International Air Transport Association (IATA), Sustainable Aviation Fuel (SAF), new technologies such as hydrogen-powered aircraft, offsets and carbon capture, and infrastructure and operational efficiencies are required to achieve lower and even net zero CO_2 emissions by 2025 [3]. However, some of these initiatives are long-term solutions as they need time and infrastructure investments to be realised [2]. Improving operational procedures has the most immediate effect on environmental benefits.

In these operational procedures, Continuous Descent Operations (CDOs) are promising as studies have shown that the environmental benefits of optimised descent operations can be up to ten times greater than those of Continuous Climb Operations (CCOs) [6]. However, the implementation of CDOs is often limited by complex and congested airspaces. These airspaces often contain procedural constraints, including runway configurations, military or civil airfields, and noise abatement procedures [7]. The amount of fuel and emissions reductions that can be achieved depends on several operational factors, including traffic density, aircraft type, and weather conditions [2]. This makes it necessary to develop flexible strategies that can stepwise mitigate constraints while maintaining operational feasibility.

Furthermore, multiple stakeholders are involved in aviation, each with different priorities and operational goals. Airlines such as KLM are primarily focused on reducing operational costs and meeting sustainability targets, while air navigation service providers (ANSP) like Luchtverkeersleiding Nederland (LVNL) are mainly focusing on safety, together with capacity and airspace efficiency. Understanding where inefficiencies occur and how to address them incrementally within existing operational frameworks is crucial to obtaining the most valuable results for all stakeholders.

This research focuses on identifying how structural and procedural airspace constraints impact aircraft vertical profiles during descent by quantifying the inefficiencies in terms of fuel consumption and CO_2 emissions. By analysing these impacts through small steps, this project aims to provide insights into how Trajectory-Based Operations (TBO) principles like CDOs can be practically applied to improve vertical flight performance in the Dutch airspace. More details on the research scope and objectives are provided in Chapter 6.

3.2. Inefficiencies

Flight inefficiencies or delays are introduced by different causes in the various flight phases [8]. This can include holding areas and holding patterns, as well as standard air routes or restricted regions, primarily as a consequence of safety [7]. Next to airspace structure, also traffic density and aircraft performance influence the trajectories of flights [2]. Inefficiencies are the reason why aircraft cannot fly according to the most optimised path from Top of Descent to the initial approach fix and cause higher fuel burn [8]. A visual representation of this deviation is portrayed in Figure 3.1. Next to this, the causes of the different vertical inefficiencies in the different flight phases are shown in Figure 3.2. In the Dutch airspace, descents are mostly influenced by:

1. Fixed arrival routes - Standard Terminal Arrival Routes (STAR)
2. Lateral constraints from airway structures
3. Air Traffic Control (ATC) influences
4. Agreements with neighboring Flight Information Regions (FIRs)
5. Military or restricted airspaces

Due to these constraints/restrictions, aircraft are forced to fly at certain Flight Levels (FL) at specific points, creating inefficiencies in the flight path of the aircraft. For example, approaching aircraft are required to enter the terminal area via an arrival fix, introducing inefficiencies and non-optimal descent trajectories [8]. Elaboration of the inefficiencies by highlighting restrictions is discussed in Section 3.3.

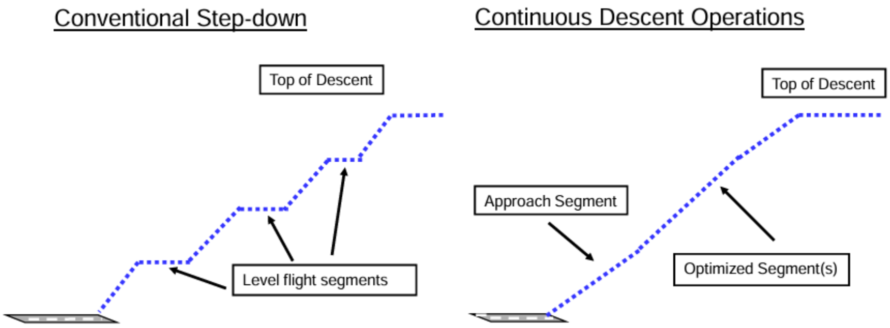


Figure 3.1: Step down approach compared to CDO [9]

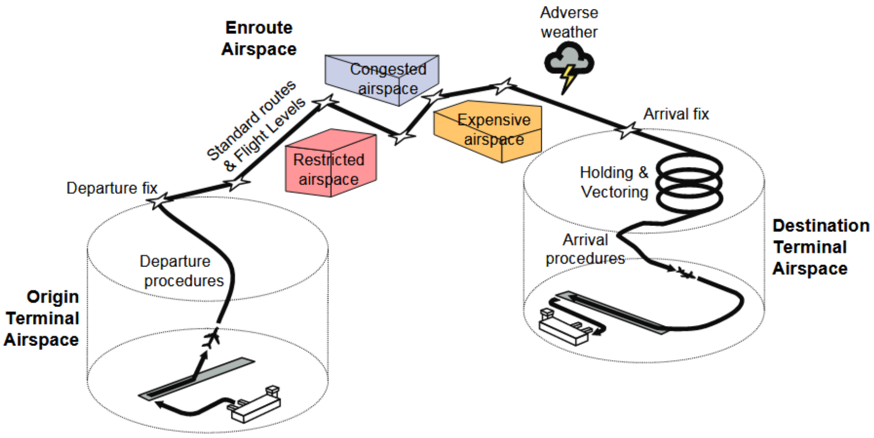


Figure 3.2: En-route inefficiency sources [10]

3.3. Restrictions

As mentioned in Section 3.2, constraints and/or restrictions cause inefficiencies which ultimately negatively impact the environment. Having an overview of what kind of restrictions are present helps identify the sources of inefficiencies. The following constraints/restrictions are applied in the Dutch airspace:

1. Altitude restriction
2. Speed restriction
3. Navigational performance requirement
4. Arrival and Departure route restrictions (Standard Instrument Departures (SIDs) and STARs)
5. Waypoint restriction
6. Restricted area constraint
7. Aircraft performance constraint
8. ATC clearances
9. Separation requirement
10. Weather constraint
11. Runway constraint
12. Noise abatement procedures

3.4. Problem Statement

Currently, in Dutch airspace, implementing fully optimised CDOs is not possible due to various constraints, both structural and procedural. This current inability indicates the need to improve the vertical approach [11] and provides an opportunity to optimise and achieve greater fuel and CO_2 savings during the descent phase. Although certain parts of TBOs and CDOs are implemented in the Dutch airspace, they are currently limited in coverage and effectiveness. Therefore, this thesis addresses how lifting specific airspace restrictions, such as border constraints, can enable CDOs through TBOs and improve the environmental performance of vertical flight operations.

4

Background Information

In this chapter, an overview of current research, technologies, and procedures supporting optimised descent operations in constrained airspace is described. This chapter is a basis for general knowledge on the research topic. First, the current technologies used in aviation relevant for this research are discussed in Section 4.1. Then, in Section 4.2, the organisation of the airspace is described. In Section 4.3, Trajectory-Based Operations are explained, after which Continuous Descent Operations are elaborated in Section 4.4. Then, the benefits of implementing these operations is detailed in Section 4.5.

4.1. Current Operational Technologies

The continuous development of operational technologies in Air Traffic Management (ATM) is the reason for the increase in automation, flight efficiency, and operational safety. The development and implementation of these technologies are driven by both technological innovation and by initiatives such as the Single European Sky ATM Research (SESAR) programme. SESAR plays an important role in the Single European Sky (SES) initiative by modernising Europe's ATM through the development and implementation of innovative operational and technological solutions that align with European Union (EU) policies [12]. Some of the technological developments are Performance-Based Navigation (PBN), Required Navigation Performance (RNP), Automatic Dependent Surveillance–Broadcast (ADS-B), 4D Trajectory Management and improved Flight Management System (FMS) capabilities. These developments are detailed in the following paragraphs.

4.1.1. Performance-Based Navigation (PBN)

PBN is the defined performance requirements for aircraft that navigate a terminal procedure or in a designated airspace, for example [13]. PBN standardises Area Navigation (RNAV) and RNP specifications around the world and minimises the amount of different navigation specifications [14]. Through PBN, flexible route planning and more efficient use of airspace are possible, which can support CDOs, ultimately reducing environmental impact [2, 15]. Furthermore, PBN supports traffic flow predictability and assists air traffic controllers in reducing the need for interventions while at the same time improving overall operational flexibility [16].

In the context of TBO, PBN is a crucial factor because it enables precise lateral path planning. This precise planning is related to more optimised vertical trajectories. Without PBN, the implementation of CDO would not be possible. So, PBN ensures the possibility of more efficient trajectories regarding airspace and aircraft performance capabilities, such as CDOs in TBOs, which is important to the analysis and discussion in this thesis.

4.1.2. Automatic Dependent Surveillance–Broadcast (ADS-B)

ADS-B is a surveillance technology in which aircraft automatically broadcast their identification, position, altitude, velocity, and other flight parameters with ground stations and other aircraft receive this information [7, 17, 18]. Under optimal conditions, aircraft can be tracked via ADS-B at distances of up to 400 km during cruise. However, the detection range decreases significantly at lower altitudes due to line-of-sight limitations. ADS-B data serves as a valuable resource for monitoring and research. However, the data may contain discrepancies such as position inaccuracies, which require appropriate filtering and validation

[6]. Furthermore, ADS-B information improves the accuracy of aircraft trajectory predictions, supporting applications in ATM and environmental impact assessments [19].

Thus, ADS-B enables real-time surveillance using GPS. This technology ensures accurate 4D trajectory tracking and improved situational awareness for ATC. The trajectory tracking is necessary to evaluate where and how inefficiencies are introduced in real descent paths. For this thesis, the simulation validation will use ADS-B combined with Flight Data Recorder (FDR) data.

4.1.3. 4D Trajectory Management and Flight Management System (FMS) Capabilities

4D Trajectory Management refers to the planning and implementation of aircraft trajectories in four dimensions: the three dimensional spatial position and time. 4D trajectories aim to optimise aircraft operations by adhering to the safety of air traffic and focus on efficiency management [16, 11]. The FMS is the onboard automation system responsible for trajectory planning [20]. An important feature of the FMS is the determination of the optimal Top of Descent (TOD), which enables idle thrust descent profiles as long as procedural and airspace constraints allow for it [21]. The FMS computes this based on parameters such as aircraft weight, weather conditions, and performance data, also taking into account speed, altitude, and time restrictions set by ATC or PBN specifications. FMS predictions are limited by onboard data availability and do not always reflect all current airspace constraints. This makes real-time trajectory management challenging.

The integration of 4D trajectory planning with improved FMS capabilities is necessary for enabling TBOs. 4D trajectory management defines the intended path of an aircraft by integrating the 4D constraints. This allows for precise planning of where an aircraft should be at any given time along its route. The FMS enables the accurate execution of that route. This is important in high-density, constrained areas like the Dutch airspace, where conflict-free and predictable operations are needed. For this thesis, these technologies are necessary to simulate and validate optimised descent paths.

4.2. Airspace Design and Structure

To better understand how the Dutch airspace is constructed, this section discusses the Dutch airspace. From a high-level to a lower-level organisation, in both lateral and vertical views, the airspace organisation is explained. First, the lateral organisation is discussed in Section 4.2.1, after which the vertical organisation is described in Section 4.2.2. Lastly, Free-Route Airspace (FRA) is discussed in Section 4.2.3.

4.2.1. Lateral Airspace Organisation

Figure 4.1 shows the FIR of the Netherlands. FIR is the largest division of airspace [22] and is called Amsterdam FIR EHAA for the Dutch airspace. The FIR has sectors which are portrayed in Figure 4.2, which different air traffic controllers manage. The FIR consists of three airspaces: controlled - B, C, D, and E, uncontrolled - F and G, and special-use/prohibited airspace, such as military zones - A. These zones and the different classification letters have different requirements, such as separation, speed limitation, and ATC clearance, for example. They are mentioned in the documents, such as the Aeronautical Information Products (AIP) of the Netherlands and other bordering countries, which are an important source of information for this thesis. Therefore, it is necessary to have an idea of what these classifications indicate. This classification can be seen in Figure 4.3.

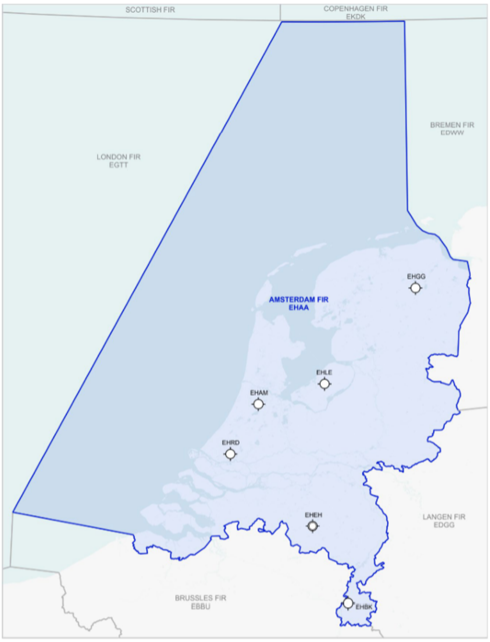
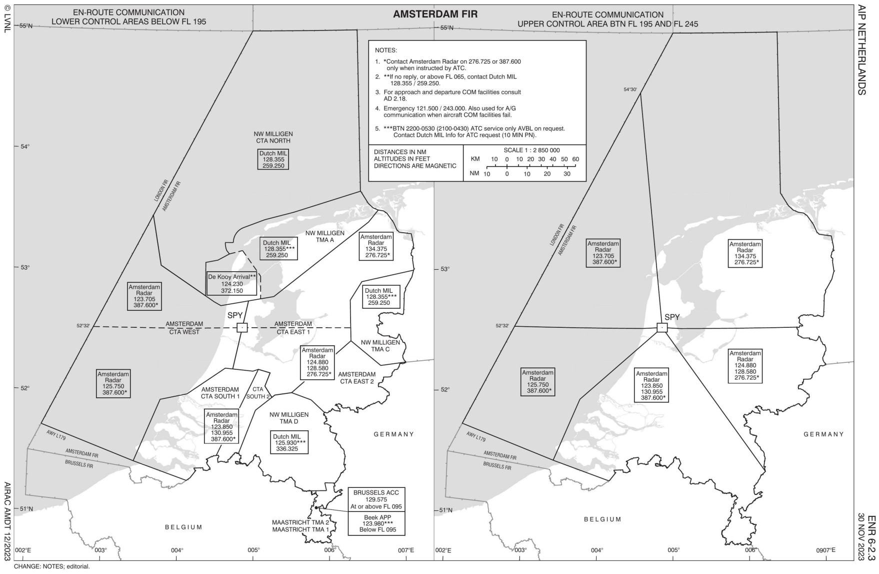


Figure 4.1: EHAA FIR [23]

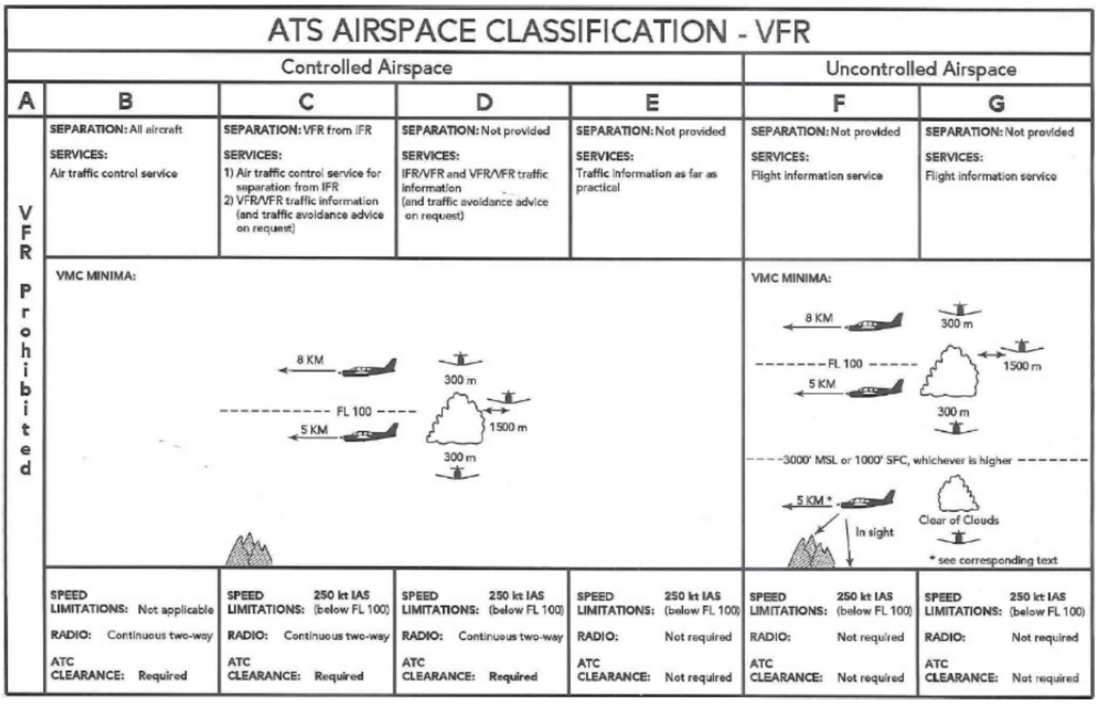

NOTES:

1. *Contact Amsterdam Radar on 276.725 or 387.600 only when instructed by ATC.
2. **If no reply, or above FL 065, contact Dutch MIL 128.355 / 259.250.
3. For approach and departure COM facilities consult AD 2.18.
4. Emergency 121.500 / 243.000. Also used for A/G communication when aircraft COM facilities fail.
5. ***BTN 2200-0530 (2100-0430) ATC service only AVBL on request. Contact Dutch MIL Info for ATC request (10 MIN PN).

DISTANCES IN NM
ALTITUDES IN FEET
DIRECTIONS ARE MAGNETIC

CHANGE: NOTES; editorial.

Figure 4.2: EHAA FIR including sector division [24]



ATS AIRSPACE CLASSIFICATION - VFR

	Controlled Airspace				Uncontrolled Airspace	
A	B	C	D	E	F	G
VFR Prohibited	SEPARATION: All aircraft SERVICES: Air traffic control service	SEPARATION: VFR from IFR SERVICES: 1) Air traffic control service for separation from IFR 2) VFR/VFR traffic information (and traffic avoidance advice on request)	SEPARATION: Not provided SERVICES: IFR/VFR and VFR/VFR traffic information (and traffic avoidance advice on request)	SEPARATION: Not provided SERVICES: Traffic information as far as practical	SEPARATION: Not provided SERVICES: Flight information service	SEPARATION: Not provided SERVICES: Flight information service
	VMC MINIMA: 8 KM 300 m FL 100 5 KM 1500 m 300 m				VMC MINIMA: 8 KM 300 m FL 100 1500 m 5 KM 300 m 3000' MSL or 1000' SFC, whichever is higher 5 KM* In sight Clear of Clouds * see corresponding text	
	SPEED LIMITATIONS: Not applicable RADIO: Continuous two-way ATC CLEARANCE: Required	SPEED LIMITATIONS: 250 kt IAS (below FL 100) RADIO: Continuous two-way ATC CLEARANCE: Required	SPEED LIMITATIONS: 250 kt IAS (below FL 100) RADIO: Continuous two-way ATC CLEARANCE: Required	SPEED LIMITATIONS: 250 kt IAS (below FL 100) RADIO: Not required ATC CLEARANCE: Not required	SPEED LIMITATIONS: 250 kt IAS (below FL 100) RADIO: Not required ATC CLEARANCE: Not required	SPEED LIMITATIONS: 250 kt IAS (below FL 100) RADIO: Not required ATC CLEARANCE: Not required

Figure 4.3: Airspace classification for controlled and uncontrolled airspaces [25]

The FIR has specific Air Traffic Service (ATS) routes, which can be called 'highways of the sky' [25]. These routes are portrayed in **??**. Apart from these routes, certain standard arrival and departure routes are also present. The arrival routes are called the STARs, which are depicted in Figure 4.4. STARs are created for noise abatement, reduction of communication between pilot and controller, separation of incoming and outgoing traffic and terrain clearance [25]. Knowledge of these routes is crucial for the analysis of the arrival traffic flows into the Dutch airspace in this thesis.

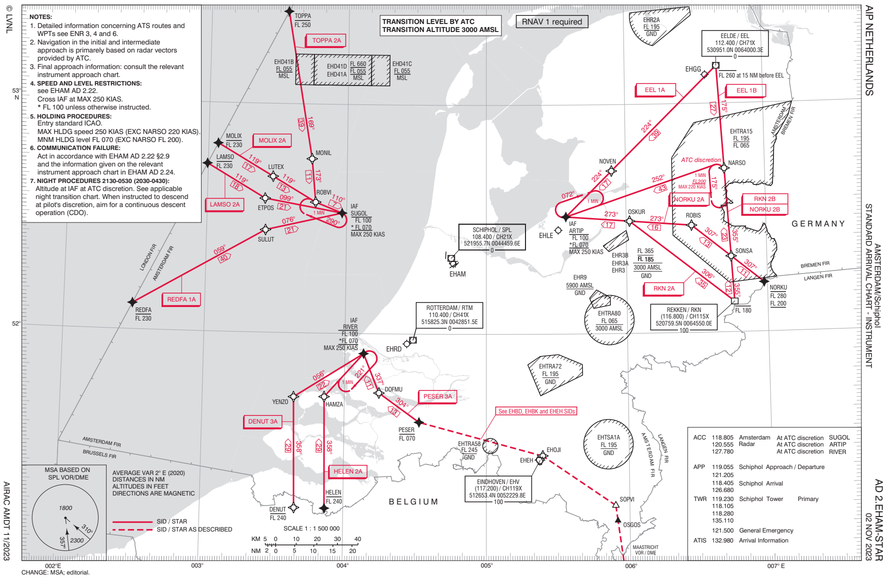


Figure 4.4: STARs of the EHAM airport [24]

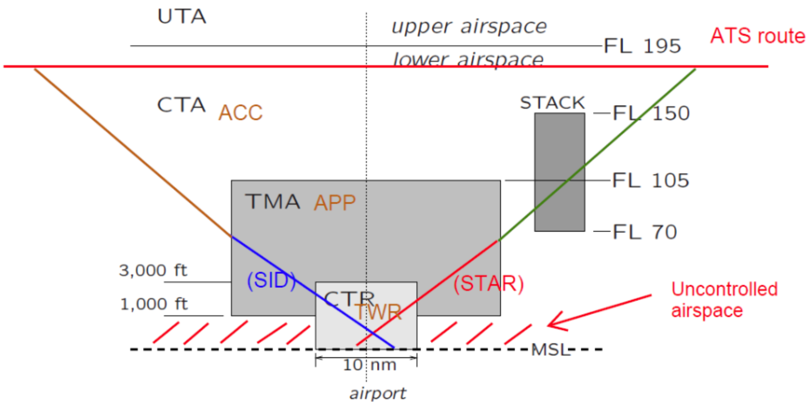


Figure 4.5: Vertical Airspace Organisation [25]

4.2.2. Vertical Airspace Organisation

All airspaces are organised in four different zones depicted in Figure 4.5, which are centralised around an airport [25]. A different group of controllers manages each zone, with each having specific requirements [22]. The parts of the airspace that are not within these areas are uncontrolled airspace. This organisation is important for the thesis as it directly influences the feasibility of CDOs. Each zone sets specific operational constraints that affect the ability of aircraft to fly the optimal descent trajectories. Knowledge of the vertical airspace structure is therefore important to understand the interactions between CDOs, ATM procedures, and potential conflicts with other traffic flows. A short explanation of the four different zones is listed below:

1. Control Area (CTR): around the airport, controlled by the Tower (TWR)
2. Terminal Manoeuvring Area (TMA): for incoming and outgoing flights, controlled by Approach/Departure Control (APP), containing SIDs and STARs
3. Control Zone (CTA): below FL245, containing holding stacks, controlled by the Area Control Center (ACC)
4. Upper Control Zone (UTA): upper airspace, at or above FL245, controlled by Maastricht Upper Air Control (MUAC)

4.2.3. Free Route Airspace (FRA)

FIR cover small sectors, usually a country, while Functional Airspace Blocks (FAB), depicted in Figure 4.6, are larger areas that are controlled by specific upper area controllers to improve the overall performance of ATM [26]. So, intergovernmental procedures are moved to a larger scale, a European framework, through the initiative of SES. Between FL245 and FL660, MUAC offers Free Route Airspace to allow airspace users to fly direct routes in this airspace [27]. Through initiatives as the FRA, aircraft are able to fly their desired optimal trajectories. Knowledge of FRA is important for assessing how flexible routing supports CDOs and increases efficiency, which will be analysed in this thesis.

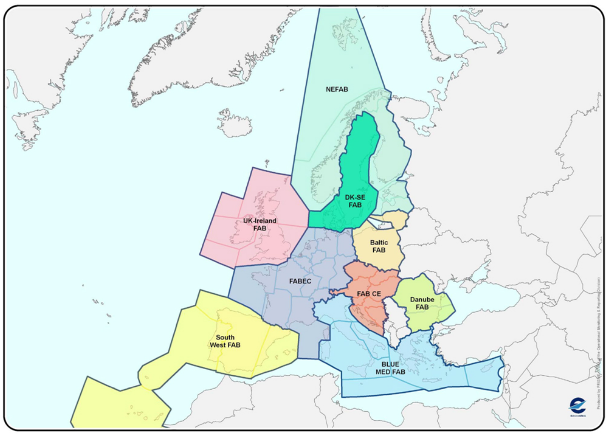


Figure 4.6: Depiction of the nine Functional Airspace Blocks dividing Europe's upper airspace [28]

4.3. Trajectory-Based Operations (TBO)

TBO is an ATM concept based on managing aircraft trajectories in four dimensions: latitude, longitude, altitude, and time [8]. TBO aims to reduce the need for interuptions by ATC procedures such as vectoring and holding patterns by increasing predictability and optimising trajectories from gate to gate [29]. TBO allows delays to be mitigated earlier in the flight, typically during the cruise phase which can reduce congestion in terminal areas. This is achieved through planning between aircraft and ATC. This planning ensures that trajectories are determined in advance and can be dynamically updated when needed. TBO enables aircraft to fly optimised descent profiles that minimise fuel burn and emissions while maintaining efficient sequencing and separation. TBOs also reduce the need for level-offs. Technologies such as PBN, ADS-B, and advanced FMS capabilities discussed in Section 4.1 are important to enable TBO by providing the necessary navigation accuracy to maintain the trajectory. TBO increases airspace efficiency, reduces controller workload, and improves environmental performance.

4.4. Continuous Descent Operations (CDOs)

CDO is an aircraft operating technique where an arriving aircraft descends continuously at its most optimal trajectory from the TOD to the final approach fix (FAF) [30, 21]. The TOD is calculated by the FMS, extending the cruise phase and delaying the start of descent to allow an idle-thrust trajectory [6]. CDOs aim to reduce vertical inefficiencies by removing level-offs, which are typical in step-down approaches designed to maintain aircraft separation in terminal airspace [7, 2].

Step-down approaches with level flight segments give air traffic controllers the flexibility to ensure safe separations. However, they introduce vertical flight inefficiencies. CDOs improve predictability by reducing controller-pilot communications and following a predefined descent path [31]. Standardised procedures are important to ensure flight safety and require knowledge of aircraft performance characteristics, airspace limitations, and environmental impacts when implementing CDO [31].

CDO is an operational technique available to aircraft operators and ANSPs to increase flight predictability and airspace capacity, while at the same time reducing noise, fuel burn, emissions, and workload. However, safety remains the primary priority, and all CDO implementations need safety assessments before operations can begin [31]. Future research and developments are expected to improve the performance potential of CDOs without decreasing capacity. This will ensure that the implementation of CDOs is valuable for sustainable ATM.

4.5. Environmental Benefits of Efficient Descent Operations

As mentioned in Section 3.1, CDOs have proven to be an effective technique to reduce the environmental impact of aircraft operations. Several studies have quantified the benefits of CDOs in terms of fuel consumption, CO_2 emissions, and noise reduction. In the following paragraph, the benefits of these efficient descent operations are highlighted.

Xue et al. [2] showed that CDOs reduce fuel consumption by an average of 139 kg per flight, equivalent to a 21.5 % reduction, while also lowering emissions of CO_2, NO_x, CO, HC, and particulate matter (PM). A nationwide adoption of CDO in China could lead to a cumulative CO_2 reduction of 67.6 million tonnes between 2025 and 2050. Similarly, Ellerbroek, Inaad, and Hoekstra [32] reported average fuel savings of 141-144 kg per flight, despite slightly longer flight durations. ter Beek [6] stated that ideal CDOs can save up to 27 % of fuel during descent, averaging around 200 kg per flight. Even high-capacity CDOs, which are designed to handle larger amounts of traffic, still offer significant fuel savings over conventional vectoring methods without compromising on arrival capacity. Olive et al. [7] emphasised that holding patterns have the highest environmental impact, while the Point Merge System (PMS) and CDO procedures, when combined, present improved efficiency. However, operational combinations of PMS and CDOs are rarely implemented.

Cecen [4] analysed flight regimes and found that optimising cruise speed and altitude can reduce CO_2 emissions by up to 4.4 %. Dalmau, Sun, and Prats [21] showed that early TOD decisions, often caused by ATC constraints and procedures, can lead to additional fuel consumption of up to 120 kg per flight. Optimising TOD positioning could therefore further improve fuel efficiency. Jaekel, Hirte, and Niemeier [11] found that level-offs below FL100 are common in dense terminal areas, with only 10.6 % of approaches flown as intended. Shifting level-offs to higher altitudes improved descent efficiency. Aksoy, Usanmaz, and Turgut [33] confirmed that 69-80 % of flights experience at least one level-off, resulting in additional fuel burn of 17-33 kg per level-off and CO_2 savings of 60-105 kg when level-offs are avoided.

Reynolds [8] identified that up to 50 % of terminal area inefficiencies stem from standard route structures, congestion, vectoring, and weather impacts. These inefficiencies can be mitigated by implementing optimised descent profiles such as CDOs. Fiala, Pilmannová, and Schmidt [16] showed that CDOs improve trajectory predictability and reduce Air Traffic Controller (ATCO) workload in low-to-medium density traffic scenarios, enabling more stable and efficient descent paths.

Overall, these studies show that efficient descent operations, and CDOs in particular, provide clear environmental benefits by reducing fuel burn, emissions, and noise while supporting airspace capacity and operational efficiency. These benefits show that continuing research and aiding to the implementation of CDOs will be beneficial. In Chapter 5, the gaps of these papers are discussed as well as the limitations present.

5

Research Gaps and Limitations

This chapter details the gaps in the literature. Next to this, the limitations of the studies are formulated. First, in Section 5.1, the research gaps are described for all the read papers one by one. Then, the limitations are discussed in Section 5.2.

5.1. Research Gaps

Although various studies have shown the environmental and operational benefits of CDOs, several research gaps remain that limit a complete understanding of their real-world implementation and performance. This section outlines the key gaps identified in the literature. The following paragraphs address these gaps in detail.

Xue et al. [2] quantified the fuel and emissions savings of CDOs but did not address safety considerations or operational challenges in high-density airspace. Modelling more complex scenarios, taking into account airspace capacity and constraints, is required to predict CDO performance in congested airspaces. Also, the operational challenges and safety considerations associated with CDOs can be analysed further.

Similarly, Ellerbroek, Inaad, and Hoekstra [32] simulated CDOs under ideal, unconstrained conditions. Ellerbroek, Inaad, and Hoekstra [32] did not account for real-world ATC interferences, which can significantly impact CDO feasibility and benefits.

del Pozo Domínguez et al. [34] identified that current efficiency metrics do not consider engine thrust levels, which leads to inaccuracies. Having limited QAR data and no validation or alternatives for ADS-B-based calculations limits the usefulness of their results. Further validation across different airspaces and aircraft types is necessary using high-fidelity data.

Fiala, Pilmannová, and Schmidt [16] focused on ATCO workload benefits of CDOs, but their results are limited because of the simulation environments. The results do not reflect the complexity of congested airspace operations. The implementation of the CDOs is not explored further. Moreover, the study discussed operational efficiency but did not look into the environmental impact of CDOs.

ter Beek [6] analysed high-capacity CDOs using ADS-B data, which contains inaccuracies. The study has no validation with real-world flight data, such as FDR data. This data will be necessary to assess fuel savings and operational feasibility in complex airspaces accurately.

Dalmau, Sun, and Prats [21] highlighted the inefficiencies caused by early TOD execution but did not investigate the root causes of these early descents. Analysis of operational practices and ATC decision-making processes is needed. Furthermore, the use of estimated aircraft mass and ADS-B data introduces inaccuracies that could be addressed by using FDR data.

Cecen [4] developed a mathematical model to estimate CO_2 emissions during cruise, but did not account for real-world procedural constraints. The study is limited to cruise operations and lacks consideration of ATC instructions and airspace restrictions that affect descent profiles.

Jaekel, Hirte, and Niemeier [11] identified that level-offs in the lower airspace are a significant source of inefficiency but did not explore how more advanced ATM concepts, such as TBOs, could mitigate these inefficiencies. Additionally, the study did not use actual fuel burn data for validation.

Aksoy, Usanmaz, and Turgut [33] demonstrated the environmental impact of level-offs during descent but focused only on shifting these segments to cruise altitude. The operational feasibility of implementing CDOs to replace level-offs was not assessed. The results are airport-specific and not validated for wider application across different airspace structures. Also, no causal analysis of why level-offs happen is conducted.

Olive et al. [7] assessed inefficiencies of holding patterns, point merges, and CDOs but did not analyse the operational causes behind these inefficiencies. The study assumes fixed landing weights and does not validate fuel estimates with actual high-fidelity data.

Finally, Reynolds [8] provided a comprehensive analysis of lateral inefficiencies in terminal areas but did not consider vertical inefficiencies or operational constraints influencing ATC decision-making. The model assumes no wind optimisation and lacks validation against real fuel and emissions data.

The reviewed studies show that research is needed which connects real-world flight data with operational constraints to understand CDO performance better. A key gap remains in identifying and quantifying the sources of descent inefficiencies in complex airspace environments. By addressing these issues, the implementation of CDOs can become more operationally feasible and effective.

5.2. Limitations

The benefits of CDOs are found in many studies, some of which are mentioned in Section 4.5. However, the implementation of these operations in real-world environments remains constrained by several limitations. The main focus of ATM is safety. This affects the implementation of new technologies and needs to be taken into account when new technologies are designed [26]. Also, many studies perform research with idealised simulations that do not reflect real-world airspace constraints, ATC interventions, or traffic complexities [32, 16]. The use of ADS-B data contains accuracy limitations due to position errors, lack of aircraft mass estimation, and missing engine performance parameters. These limitations impact fuel and emissions estimation reliability [7, 6]. Additionally, validation with high-fidelity FDR data is often missing, limiting the credibility of fuel-saving assessments [21].

Furthermore, operational factors such as the reasons for early descents, level-offs, and ATC decision-making processes are often overlooked [21, 11]. Safety considerations, including the challenge of sequencing aircraft with varying descent profiles and deceleration rates, remain an important limitation to CDO implementation [6, 26]. Lastly, large-scale comparative studies assessing environmental inefficiencies across multiple airports and procedures are limited, and the complexity of integrating CDOs into existing air traffic management systems has not been fully addressed [7, 8].

6

Research Objective and Methodology

This chapter discusses what the research topic will be. In this chapter, from the gaps identified in Chapter 5, the objectives are clarified and the methodology is chosen. First, the primary objective of the research is provided in Section 6.1. Then, in Section 6.2, the research main and sub-questions are phrased. Then, in Section 6.3, the hypotheses are formulated. Lastly, the methodology for this research is explained in Section 6.4.

6.1. Research Objective

The primary objective of this thesis is to improve vertical flight performance by quantifying and mitigating operational inefficiencies through the application of CDO in the TBO framework, with a particular focus on the descent phase of flight. The study will focus on the Dutch airspace, where a high density of traffic and airspace constraints contribute to operational inefficiencies. By identifying the sources of the inefficiencies, this thesis aims to support the development of more feasible CDO procedures within a TBO framework. Furthermore, this thesis aims to provide stakeholders such as airlines like KLM and ANSP like Luchtverkeersleiding Nederland (LVNL) with high-fidelity insights and utility to support decision-making on procedural constraints and performance improvements in TBO operations. To achieve this objective, the main research question and guiding sub-questions are formulated in Section 6.2.

6.2. Research Question and Sub-Questions

To conduct the thesis formulated in Section 6.1, a main research question is created together with assisting sub-questions. The main research question is meant to address the overall aim of the thesis. The sub-questions provide structure and focus to the research process. By answering these sub-questions, a complete response to the main research question will be achieved. In Section 6.3, the expected outcome of these questions is discussed.

6.2.1. Main Research Question

To what extent can vertical efficiency during the descent phase of arrival traffic into the Dutch airspace be improved by modifying current procedural constraints?

6.2.2. Sub-Questions

For the sub-questions, the most important parts of the research question are addressed. These parts are listed in three main topics: operational implementation, performance impact, and constraint analysis. The different sub-questions of these different parts are listed below.

Operational Implementation of CDO

1. What are the operational principles of Continuous Descent Operations (CDOs) within the Trajectory-Based Operations (TBO) framework?
2. How are CDOs currently implemented in traffic flows into the Dutch airspace?
3. Which technologies are essential to enable efficient CDOs in trajectory-based oriented flows?

Performance Impact (Fuel & Emissions) of CDO implementation

1. How are fuel consumption and CO_2 emissions estimated?
2. How does improving vertical trajectory efficiency through CDOs affect fuel consumption and CO_2 emissions compared to current step-down approaches?
3. What are the estimated fuel savings and emission reductions per flight when switching from stepped descents under current airspace constraints to CDOs for traffic flows into the Dutch airspace?
4. How does the stepwise removal of specific constraints/restrictions influence fuel savings and environmental benefits, when modelled under varying success rates of implementation, for example 10 %, 30 %, or 50 % adoption?

Airspace Constraints and Vertical Inefficiency

1. What are the primary sources of vertical inefficiencies during descent within arrival traffic flows of the Dutch airspace?
2. How to assess the impact of a specific constraint?
3. How to validate the impact of removing a specific constraint?
4. Which specific airspace constraints/procedures most significantly restrict optimal CDO implementation in traffic flows into the Dutch airspace?

6.3. Hypotheses

The implementation of CDOs within the TBO framework in the Dutch airspace is expected to have a positive impact on the environmental performance of aircraft. By mitigating vertical flight inefficiencies caused by airspace constraints, the implementation of CDOs will reduce fuel consumption and CO_2 emissions during descent. However, the total amount of environmental benefits depends on the level of airspace flexibility, the operational constraints, and the availability of technologies that enable these operations. The feasibility of achieving optimal CDO trajectories is further influenced by traffic density and real-world operational considerations. Also, the success rate of flights achieving optimal CDOs will improve with increased airspace flexibility.

6.4. Proposed Methodology

To investigate the impact of lifting airspace restrictions on vertical flight performance, a stepwise simulation-based method will be used. This method will show a clear comparison between the current baseline operations, constrained by existing procedural limitations, and an optimised case that represents ideal CDO trajectories through TBOs. Next to showing this comparison, the sources of the inefficiencies will be shown. By identifying the sources of inefficiencies, the stepwise simulation can be built to see the possibilities.

The simulation will be performed in BlueSky, where current airspace structures and procedural constraints will be used to represent current descent profiles. Optimised scenarios will then be created by incrementally lifting these constraints, allowing for CDOs in line with TBO principles. The influence of each constraint adjustment will be assessed to understand its individual and added effect on vertical efficiency.

To quantify the environmental impact of these improvements, fuel consumption and CO_2 emissions will be calculated using OpenAP performance models. These calculations will be integrated into the simulation workflow, enabling both visual and numerical assessment of the operational benefits achieved through procedural optimisations.

Model validation will be conducted using FDR data from actual descent operations within the Dutch airspace. The validation process will compare simulated baseline trajectories against real-world flight profiles. This will ensure that the model accurately represents current operational performance.

In addition to assessing fuel and emissions savings, the methodology will evaluate the success rate of the optimal trajectories. Specifically, looking at the proportion of flights that can follow the most efficient vertical profile under varying constraint scenarios. A sensitivity analysis will be performed to understand how factors such as airspace flexibility, traffic density, and aircraft type influence the feasibility and environmental impact of CDO implementation.

The final model will ideally serve as a decision-support tool, providing stakeholders with an indication of the trade-offs between current procedural constraints and optimised descent operations. By combining simulation results with real-world operational inputs from airlines, the study will deliver valuable insights on how incremental procedural adjustments can enhance vertical flight efficiency and reduce emissions of airline operations. The research will start in the South of the Dutch airspace, and if time allows, extension to different areas can be achieved.

7

State of the Art and Paper Overview Table

In this chapter, the current state of the art, an overview of the different papers reviewed for this literature review and a separate overview of the various measures are provided. The state of the art focuses on the continuous descent operations and vertical efficiency in current operations. In the paper overview, the most essential points of the literature are stated, containing information on the research, methods, outcomes, and gaps. Having this overview quickly clarifies what has been done and what still needs to be researched. The overview table is structured so that the more meaningful papers are listed at the top, with less essential papers going down in the table. First, the state of the art is established in Section 7.1. Then, in Section 7.2, the overview table is presented. Lastly, in Section 7.3, the different approaches gathered from the literature are presented in a table.

7.1. State of the Art

Research on descent operations has focused on the potential to improve fuel efficiency, reduce emissions, and support more sustainable ATM. Various studies showed that CDOs reduce fuel consumption with corresponding CO_2 savings. These benefits are most significant under ideal conditions, but are also present in congested airspaces. CDOs allow aircraft to descend at (near) idle thrust while minimising level segments.

The environmental benefits of CDOs are known, but operational constraints hinder the implementation of CDOs. In low-traffic conditions, optimal CDOs can be applied. However, in congested airspaces, ATCOs usually rely on vectoring, sequencing, and level-offs to maintain capacity and safety. This introduces vertical inefficiencies as the descent is interrupted, which reduces the fuel and emission benefits of CDOs. Research shows that level-offs below 10,000 feet are common in European and global operations. The level-offs are driven by these ATC procedures or airspace structure, for example.

Another source of inefficiency is an early TOD. When descents are initiated too early, aircraft use extra fuel compared to optimal trajectories. These early descents are usually due to conservative flight planning or a lack of specific ATCO knowledge of the TOD calculated by the FMS. Also, arrival procedures such as holding patterns and point merges add environmental costs. Although the point merge system and CDOs are improvements in comparison to conventional vectoring, they are not always optimally implemented in current operations.

Also, analyses of lateral inefficiencies and airspace structure show the role of ATM design in improving flight efficiency. Inefficient routing, restricted airspace, and a lack of flexibility in SIDs and STARs contribute to unnecessary fuel burn. Recent operational concepts such as FRA and TBO aim to address these inefficiencies by allowing more direct and predictable trajectories.

In summary, the state of the art shows that operations such as CDOs have clear environmental and operational benefits. However, traffic density, ATC procedures, and airspace design limit their benefit in the real world. Through improving efficiency metrics, validating results with more accurate flight data, and exploring advanced ATM concepts, current research aims to address these limitations. This could lead to an improvement in vertical efficiency still maintaining safety and capacity. In Section 7.2, a more detailed summary of the topics and outcomes of different studies is presented for all papers reviewed.

7.2. Papers Overview Table

Paper	Main Topic	Methods	Outcome	Gaps
Xue et al. [2]	The study investigates the environmental and operational benefits of CDOs in aviation, focusing on how they reduce fuel consumption and aircraft emissions compared to step-down approaches.	An estimation method for fuel consumption and emission reductions through CDOs compared to the step-down approach. Validation was performed using QAR data from 7 major Chinese airports.	Fuel savings: On average, CDOs reduce fuel consumption by 139 kg per flight, 21.5 % per flight also reducing emissions of CO_2 and other pollutants such as NO_x, CO, HC, and PM. Long-term impact (2025–2050) for a nationwide adoption in China could lead to a cumulative CO_2 reduction of 67.6 million tonnes.	Analyse the challenges for safety considerations that are associated with CDOs. More advanced modelling to predict the performance of CDOs in different scenarios.
ter Beek [6]	This paper investigates how CDOs can be applied in high traffic density environments and what the maximum possible impact of these procedures is.	With ADS-B data, CDOs for arrival traffic at Amsterdam Schiphol Airport (EHAM) is simulated in BlueSky using BADA focusing on vertical optimisation, lateral optimisation and combined for five different scenarios.	Ideal CDOs save the most fuel, around 27 % for the descent flight, averaging around 200 kg, and high-capacity CDOs still save significantly better than conventional, around 10 % and around 237 kg of CO_2 emissions per flight. The high-capacity CDO approach had no loss of arrival capacity compared to vectoring. Speed control instead of vectoring or level-offs offered greater predictability and smoother flows. High-capacity CDOs are less fuel-efficient than ideal CDOs, but they offer significant gains over current practices without losing capacity.	Used ADS-B data for the analysis, however, this contains a lot of inaccuracies. Using real-world flight data would be beneficial for the analysis of Continuous Descent Approaches (CDAs). The implementation is complex. Further research into real-world constraints, looking into ATC and complex airspace constraints, is necessary.

Aksoy, Usanmaz, and Turgut [33]	This paper investigates how level-offs during descent impact fuel consumption, emissions, and flight time. It focuses on shifting these segments to cruise altitude to improve efficiency.	Used real FDR data of 412 flights at 3 Turkish airports. Developed an algorithm to detect level-offs. Calculated fuel, time, and emissions savings if level-offs were replaced with cruise segments. Boeing Fuel Flow Method 2 (BFFM2) used for emissions.	Found 69-80 % of flights had at least one level-off varying per airport. Average fuel savings per level-off: 17-33 kg. CO$_2$ savings: 60-105 kg. HC and NO$_x$ savings were found to be insignificant. RNAV and conventional procedures affect flight efficiency in TMA.	Focuses only on shifting level-offs to cruise, doesn't assess the operational feasibility of CDO implementation. No causal analysis of why level-offs happen operationally. Results are airport-specific and lack validation for wider airspace structures.
Olive et al. [7]	Assesses the environmental inefficiencies both fuel and emissions of arrival procedures such as holding patterns, point merge, and CDOs at five European airports.	Analysed two months of ADS-B data at five different airports with automated detection of procedures. Fuel and emissions were estimated using OpenAP performance models. Applied bootstrapping to compare inefficiencies of both fuel & emissions between procedures and airports.	Holding patterns have the highest negative environmental impact. Point merges and CDOs perform better but are not optimally combined. EHAM shows higher CDO usage and better efficiency than Heathrow (EGLL). Combining point merge and CDOs is rarely achieved operationally.	The study doesn't explore the operational reasons behind inefficiencies only outcome analysis. No validation with actual fuel burn data like FDR. Assumes 90 % landing weight for all aircraft, which introduces inaccuracies. Focus is on statistical comparison, not operational feasibility of improvement strategies.
Ellerbroek, Inaad, and Hoekstra [32]	This paper investigates the fuel benefits by comparing fuel consumption based on historical flights with real and simulated CDO flights for the year 2015. The fuel and emission reduction potential of CDOs at Schiphol International Airport is studied, analysing the effects of implementing 100 % CDOs.	The study used Aircraft Condition Monitoring System (ACMS) data and ADS-B data to model historical flights. The fuel-optimal profile was simulated and compared to the actual flight. Fuel use was calculated using the EUROCONTROL BADA 3.12 model	CDO flight have longer flight duration byt lower fuel consumption. CDO flights save 141-144 kg of fuel per flight.	CDOs were simulated under ideal, unconstrained conditions meaning that real-world air traffic constraints weren't modeled. Real-world implementation requires looking at these constraints.

Jaekel, Hirte, and Niemeier [11]	The paper lookst at ATC practices and airspace structure affect vertical efficiency in the lower airspace, identifying vertical flight inefficiencies in current descent operations at Frankfurt airport.	Used a large dataset of trajectory data from commercial flights at multiple European airports. Defined metrics to assess vertical approach inefficiency include number and duration of level segments, altitude profile deviations, estimated fuel/emissions. Used a statistical methods to link inefficiencies to specific ATC procedures and traffic complexity levels.	Level-offs below FL100 are frequent, especially in dense terminal areas, only 10.6 % of approaches flown as intended. ATC interventions, such as vectoring and sequencing, are major contributors as well as weather influences. Shifting unavoidable level-offs to higher altitudes improved efficiency.	Focuses on identifying inefficiencies but lacks investigation into mitigation strategies. Does not validate fuel savings with actual FDR data. Limited exploration of how advanced ATM concepts like TBO could improve vertical efficiency.
Reynolds [8]	This paper quantifies lateral flight inefficiencies globally for enroute and terminal areas, linking inefficiency sources like airspace structure, congestion, and weather to environmental impacts. It aims to inform ATM system design for SESAR/NextGen.	Developed lateral inefficiency metrics comparing actual trajectories to great circle distances. Analysed flight data from FAA radar tracks, airline FDR in Europe, and MOZAIC in Africa/Asia. Explored inefficiency patterns across flight phases and regions.	Found significant inefficiencies in terminal areas (up to 50% of total inefficiency). Restricted airspace and standard route structures were the biggest inefficiency sources (27 %). Congestion, vectoring, and weather impacts were quantified.	Focuses only on lateral inefficiencies, no vertical inefficiencies were assessed. It is a simplified model asssuming no wind optimisation for oceanic airspace. No causal analysis of operational decisions behind inefficiencies. Lacks validation against actual fuel/emissions data.

Dalmau, Sun, and Prats [21]	This study analyses how the early execution of TOD points in commercial flights leads to fuel inefficiency and increased emissions, characterising the inefficiencies, proposing a method to identify early descents, and applying the method to a case study.	In this paper, early descents are simulated for an Airbus A320 using the trajectory computation tool from Airbus Performance Engineering Programs (PEP). Using ADS-B surveillance data from real flights, insights into early descents and fuel inefficiencies are produced.	Early TODs are common, especially under ATC constraints or conservative flight planning. Caused by ATCO not knowing the exact position of TOD by FMS and safety. Extra fuel consumptions due to an earlier TOD are up to 120 kg per flight depending on aircraft and conditions. Factors like airspace structure, traffic load, and procedural habits contribute to early TOD decisions. Optimising TOD could lead to notable fuel and CO_2 savings on a system-wide scale.	No analysis into causes for early descents was done. Analysing operational inefficiencies can help with potential mitigation possibilities. Aircraft mass is estimated, and ADS-B data is used. Having more accurate data like FDR data to validate is necessary to increase accuracy.
Fiala, Pilmanová, and Schmidt [16]	The paper investigates how the implementation of CCO and CDO affects ATCO workload.	Conducted and evaluated real-time simulation experiments with ATCOs using various traffic scenarios involving CCOs, CDOs, or conventional operations. Tested different traffic densities to simulate realistic operational environments.	This paper shows that implementing the CCO and CDO has a positive effect on the capacity management of the (Dutch) airspace. Trajectory predictability and fewer level-offs improve strategic planning and reduce communication load. CDOs and CCOs can reduce ATCO workload, especially in low-to-medium traffic density scenarios. In high-density traffic, the workload benefits are less due to limited flexibility to resolve conflicts and increased coordination to accommodate continuous profiles.	Results based on simulation, not live operations. Current simulations do not reflect more complex or congested environments, and no exploration into automated support tools that could mitigate workload under high-traffic CDO/CCO scenarios. Integration with traffic flow management tools and machine learning-based conflict prediction to support ATCOs can be explored.

del Pozo Domínguez et al. [34]	This paper evaluates performance metrics for measuring CDO fuel efficiency using QAR and surveillance data. It proposes refined metrics to improve accuracy.	Analysed operational efficiency of over 1700 flights across different aircraft types and regions using QAR data. Evaluated EUROCONTROL's BADA model and proposed a fuel penalty estimation metric that uses level-offs and engine thrust activity. Also, tested alternative metrics for public surveillance data.	Time in level flight often incorrectly classifies inefficient flights. The proposed fuel penalty metric provides more accurate insights. Alternative public data metrics, such as Rate of Descent, showed stronger correlation with actual fuel inefficiencies than current methods.	Current CDO definitions and metrics do not take into account engine thrust levels, leading to overestimation of efficiency. Alternative metrics from public data need improvement to better approximate real fuel efficiency. Further validation is needed with more QAR datasets and different airspace/aircraft configurations.
Dekker [26]	This paper introduces the concept of “Free Airspace” as a potential solution for the congestion in the European Airspace/Airspace capacity issue which decreases the number of delays, increases efficiency and reduces excess fuel burn and the emissions.	This paper proposes a redesign of current air traffic management structures. An analysis of current ATM structures, including FABs, entry points, and route constraints, with simulation of three scenarios: 1. standard route using SIDs, STARs, and waypoints. 2. SID and STAR only, no en-route waypoints. 3. Direct routing (no SIDs, STARs, or waypoints). Analysed time, fuel, and distance savings.	Significant reductions in fuel and time consumption can be achieved by operating flights on direct routes, disregarding any restrictions imposed by politics or the environment. Direct routing significantly reduces flight time, fuel consumption, and distance with up to 22 % of time saved, up to 21.5 % of fuel saved, and up to 30 % of distance reduced. Simplifying routes by eliminating SIDs/STARs and waypoints yields limited benefits for short flights, but substantial for longer routes. Simulation supports the environmental and operational efficiency gains of Free Airspace.	Geopolitical, environmental, and geographic constraints can be further explored for practical implementation. Limited flight simulation samples and safety and operational control in a Free Airspace environment require further investigation.

Cecen [4]	This paper aims to calculate the CO_2 emission for three different en-route flight regimes using a linear regression equation. It introduces a linear regression equation to calculate the total CO_2 emissions the aircraft produces during the cruise phase of flight using the information of initial weight, initial air density, initial airspeed, initial lift coefficient, distance, aircraft type and flight regime.	Using different types of aircraft, six most commonly used narrow-bodies, to collected performance data to estimate CO_2 emissions. Used linear regression analysis to model CO_2 emissions as a function of True Air Speed (TAS), Altitude, Aircraft weight, Outside air temperature, Engine type/fuel flow.	The constant airspeed and lift coefficient regime has the least emissions. The flight regime with constant altitude and lift coefficient produces approximately 1.6 % more CO_2 emissions and the constant altitude and airspeed flight regime has approximately 4.4 % more. Results suggest optimising cruise speed and altitude can lead to substantial emission reductions without hardware changes.	Mathematical model that focus on cruise phase only. The real-world operations are not considered, where they need to take into account procedural constraints such as airspace constraints or ATC instructions. FDR data can be used to validate the aircraft's performance to increase accuracy.

7.3. Measures Overview Table

The literature reviewed for this thesis presents different methodological approaches. Some are data-driven analyses using FDR data and ADS-B, and other studies are simulation-based with performance models such as Base of Aircraft Data (BADA) or OpenAP. Also, the papers have different scopes. For example, some quantify additional fuel burn and emissions from level-offs or early descents, and some assess inefficiencies caused by airspace structure, ATC interventions, or procedural design. The following table provides an overview of these different approaches, with the calculation methods and data sources used.

Paper	Approach	Calculations	Data Used
Xue et al. [2]	Analysis of environmental and operational benefits of CDO through additional fuel consumption calculations for level-off segments and the extended cruise phase of CDO.	***Fuel:*** Extra fuel consumption for level-offs: $F^* = F1 + F2 + F3$, with extra vertical distance flown: $D^* = D1 + D2 + D3$ (for 3 level-off segments) Extra fuel for extended cruise phase (using the average values at TOD altitude): $F^* = \frac{D^* \bar{f}^*}{v^*}$, where $\bar{f}^*$ and v^* are the average fuel flow and ground speed at TOD altitude Additional fuel consumption due to level-offs: $F = F - F^*$ ***Emissions:*** $EM_k = F * E_k$, where F is the fuel consumption and E_k the emissions index of the pollutant k to calculate the amount of aircraft emissions of pollutant k (EM_k) ***Future fuel consumption and emissions for year y:*** $F_y = F_{2024} a_y (1 - b_y)(1 - c_y)(1 - d_y)$, rates ay, by, cy, and dy denoted in the paper of waypoint 2025 [35] $W_y^k = F_y (1 - e_y) E_k^f + F_y e_y E_k^f R_k$, where e_y is a rate also denoted in the paper of waypoint 2025 [35] and R_k is the emissions factor of pollutant k to calculate the emissions of pollutant k in year y (W_y^k Other parameters noted in the paper	Quick Access Recorder (QAR) data of 7 airports in China of 16 different aircraft models (12,582 flights total) Parameters related to aircraft performance and flight operations, such as altitude, true airspeed, heading, vertical speed, and ground speed. Aircraft positions using latitude and longitude, engine performance metrics such as thrust settings and fuel flow, and wind direction and speed.

Paper	Approach	Calculations	Data Used
Ellerbroek, Inaad, and Hoekstra [32]	CDO of 25 constant Flight Path Angle (FPA) idle descent profiles simulations per aircraft type based on historical flights, with the output fuel benefits from fuel-optimal CDOs selecting this fuel optimal. Fuel consumption is determined by integrating fuel flow over time using performance coefficients from BADA 3.12.	***Fuel:*** Fuel flow: $f = \eta Thr$ with $\eta = C_{f1}(1 + \frac{V_{TAS}}{C_{f2}})$ where f is the fuel flow, Thr the thrust, η the thrust specific fuel consumption, V_{TAS} the true airspeed and C_{f1} and C_{f2} the BADA fuel coefficients Thrust: $Thr = \frac{mg_0}{V_{TAS}}\frac{dh}{dt} + m\frac{dV_{TAS}}{dt} + D$, where m is the aircraft mass, $g0 = 9.80665 m/s2$ is the gravitational acceleration, h is aircraft altitude, and D is aircraft aerodynamic drag. Fuel consumption is calculated by integrating fuel flow over time. 25 idle descent profiles simulated per flight with varying FPAs. Fuel-optimal CDO selected and compared to a historical flight. Annual fuel savings extrapolated using median savings per aircraft type. ***Emissions:*** CO_2 emissions are calculated linearly from fuel savings.	Data covers 98 % of arrivals at Schiphol in 2015. Study assumes idle thrust and constant FPA for CDOs.
del Pozo Domínguez et al. [34]	Assessment of CDO fuel efficiency using QAR and surveillance data. Development of new metrics, including fuel penalty and calibration of aircraft performance models.	***Fuel:*** Fuel flow modeled using BADA Total Energy Model (TEM): $Thr - Dv_{TAS} = mg_0\frac{dh}{dt} + mv_{TAS}\frac{dv_{TAS}}{dt}$ Fuel penalty metric: 1. Penalty from level-offs: simulate continuous descent by shifting level segments to cruise altitude. 2. Penalty from non-idle thrust: simulate idle descent using calibrated BADA models. Iterative simulation ensures horizontal distance matches actual flight. $FP_{kg} = FB_{actual} - FB_{simulated}$, where FP is the Fuel Penalty and FB the fuel burned FP (%) $= \frac{FP(kg)}{FB_{actual}} \times 100$ ***Emissions***: Not directly modelled, but the fuel penalty is used as a measure of emissions inefficiency.	QAR data from over 1700 flights across four tail numbers (narrow- and wide-body aircraft). Surveillance data (ADS-B) is used for alternative metrics. BADA 4 performance models calibrated per tail number. Metrics include time in level flight, rate of descent (ROD), and descent duration.

Paper	Approach	Calculations	Data Used
ter Beek [6]	Simulation-based analysis of CDOs with FPA of 2.5 under high-capacity conditions at Schiphol using Bluesky and BADA performance data	***Fuel:*** Fuel flow modeled using BADA Total Energy Model: $T{-}DV_{TAS} = W\frac{dt}{dh} + mV_{TAS}\frac{dV_{TAS}}{dt}$, where W is aircraft weight, and h the altitude. $D = C_d \cdot \frac{1}{2}\rho V_{TAS}^2 S$ with the drag coefficient $C_d = C_{d0} + kC_l^2$ and with the lift coefficient $C_l = \frac{mg_0}{\frac{1}{2}\rho V_{TAS}^2 S \cos(\phi)}$ For the fuel flow nominal: $\eta = \frac{C_{f1}}{1+V_{TAS} \cdot C_{f2}}$ with $f_{\text{nom}} = \eta \cdot \text{Thrust}$ And fuel flow idle: $f_{\text{min}} = C_{f3}\left(1 - \frac{H_p}{C_{f4}}\right)$ Descent distance based on flight path angle: $d_{\text{descent}} = \frac{h_{\text{cruise}} - h_{\text{approach}}}{\tan(\gamma)}$ Constant deceleration during descent: $a = \frac{V_{\text{cruise}}^2 - V_{\text{approach}}^2}{2 \cdot d_{\text{descent}}}$ Velocity update per segment: $V_{i+1} = \sqrt{V_i^2 + 2ad}$ Vertical speed per segment: $V_z = \frac{V_i + V_{i+1}}{2} \cdot \sin(\gamma)$ And Separation and path extension to maintain separation at the FAF, aircraft are delayed by extending their cruise phase: Extended radius of FAF circle: $R_2 = R_1 + \frac{V \cdot t_2}{1+\theta}$, where R_1 is the original FAF radius. t_2 is the required delay time, θ is the angular travel along the circle	ADS-B data from busy summer days in 2019 at EHAM Wind data from Global Forecasting System (GFS). Aircraft weight distributions from Bouwels [36]. Simulations using Bluesky

Paper	Approach	Calculations	Data Used
Fiala, Pilmannová, and Schmidt [16]	Simulation-based assessment of the impact of CCO and CDO on ATCO workload using the RAMS Plus fast-time simulation tool and Eurocontrol's BADA performance model.	***Fuel:*** Total Energy Model (BADA): $T-D\cdot V_{TAS} = W\cdot\frac{dh}{dt}+m\cdot V_{TAS}\cdot\frac{dV_{TAS}}{dt}$ with $D = C_d\cdot\frac{1}{2}\rho V_{TAS}^2 S$ and $C_d = C_{d0}+kC_l^2$ and $C_l = \frac{m\cdot g_0}{\frac{1}{2}\cdot\rho\cdot V_{TAS}^2\cdot S\cdot\cos(\phi)}$ Thrust-Specific Fuel Consumption (TSFC): $\eta = \frac{C_{f1}}{1+V_{TAS}\cdot C_{f2}}$ Nominal Fuel Flow: $f_{\text{nom}} = \eta\cdot T$ Idle Fuel Flow: $f_{\text{min}} = C_{f3}\left(1-\frac{H_p}{C_{f4}}\right)$ Descent Distance: $d_{\text{descent}} = \frac{h_{\text{cruise}}-h_{\text{approach}}}{\tan(\gamma)}$ Deceleration: $a = \frac{V_{\text{cruise}}^2-V_{\text{approach}}^2}{2\cdot d_{\text{descent}}}$ Velocity Update: $V_{i+1} = \sqrt{V_i^2+2ad}$	Simulated traffic scenarios based on real European airspace structure Aircraft performance from BADA v3.12 Traffic samples from EUROCONTROL Wind and weather conditions are assumed to be constant for baseline comparison
Aksoy, Usanmaz, and Turgut [33]	Analysis of vertical profile inefficiencies during descent using FDR data. Fuel burn, emissions, and flight time are compared between actual descent profiles and ideal CDOs.	Level-off Detection Criteria: Altitude threshold: Level-off must occur below 25,000 ft. Altitude/FPA change threshold: Instant altitude change within ±10 ft or FPA change between 0 – 0.35. Duration threshold: Level-off must last ≥ 20 s (≥60 s for benefit analysis). Fuel and Emissions Calculations: Specific Range: $SR = \frac{\text{Distance}}{\text{Fuel Burned}}$ Used to compare efficiency of low-level vs. cruise segments. ***Emissions:*** With BFFM2: $Emission_x = E_n\cdot EI_X\cdot TIM\cdot FF$, where E_n = number of engines, EI_X = emission index for pollutant X, TIM = time in mode and FF = fuel flow	FDR data of 412 flights from SAW to ESB, AYT, BJV airports od 24 aircraft of the same type Aircraft type: narrow-body twin-engine with CFM56-7B26E engines Emissions data from the ICAO databank

Paper	**Approach**	**Calculations**	**Data Used**
Olive et al. [7]	Analysis of environmental inefficiencies in arrival procedures at five major European airports using ADS-B data and the OpenAP aircraft performance model. Procedures studied include holding patterns, point merge, and CDO.	***Fuel and Emissions:*** Fuel and emissions are estimated using the OpenAP model: $Emission_x = E_n \cdot EI_X \cdot TIM \cdot FF$ Procedure Identification: CDO detection: A trajectory is labelled as CDO if level segments are <0.5 % of descent duration. Point merge detection: Identified via constant-distance legs followed by a DIRECT segment to the merge point. Holding pattern detection: Neural network-based classification using the traffic library. Inefficiency Quantification: Bootstrapping method: Used to compare fuel consumption distributions between flights with and without a procedure. Normalised metrics: Fuel and emissions normalised by TMA radius 50 nm for EGLL and EHAM for example.	ADS-B data from OpenSky Network for October – November 2019) Airports: EGLL, EGLC, EIDW, LFPG, EHAM Aircraft types matched via OpenSky and OpenAP databases Mass assumed at 90 % of maximum landing weight
Jaekel, Hirte, and Niemeier [11]	Analysis of vertical approach efficiency in the lower airspace using trajectory data from Frankfurt Airport. Two metrics are developed: Vertical Flight Inefficiency (VFI) and 3-Degree Efficiency (3DE). Regression models (MM and Tobit) are used to identify determinants of inefficiency, focusing on ATC decisions.	Vertical Efficiency Metrics: VFI: $VFI_k(t) = \frac{\text{Level-off time}}{\text{Total flight time in TMA}}$ with Level-off defined as no descent for > 40 seconds and VFI $\in$ [0, 1] with lower values indicating higher efficiency 3DE$_k(t) = \frac{\text{Time flown within } 2.5^\circ\text{–}3.5^\circ \text{ descent corridor}}{\text{Total flight time}}$ Based on the ICAO standard descent angle. 3DE $\in$ [0, 1] with higher values indicating better alignment with the optimal descent profile	ADS-B data of more than 58,000 flights at Frankfurt Airport in 2019

Paper	Approach	Calculations	Data Used
Cecen [4]	Linear regression analysis using simulated cruise phase data for six narrow-body aircraft types across three flight regimes. The study estimates CO_2 emissions based on initial flight parameters and evaluates the environmental impact of different cruise strategies.	***Fuel:*** Drag Coefficient: $C_D = c_{d0} + k \cdot c_L^2$ where $k = \frac{1}{\pi \cdot e \cdot AR}$ $T = C_D \cdot \frac{1}{2} \cdot \rho \cdot V_{\text{TAS}}^2 \cdot S$ Fuel flow nominal:$f_{nom} = \eta \cdot T$ Fuel flow cruise:$f_{cr} = C_{fcr} \cdot \eta \cdot T$ TSFC: $\eta = C_{f1} \cdot \left(1 + \frac{V_{\text{TAS}}}{C_{f2}}\right)$ ***Emissions:*** $CO_2 = 3.16 \cdot$ Fuel Burn Regression Model: $CO_2 = \beta_0 + \beta_1 \cdot W + \beta_2 \cdot \rho + \beta_3 \cdot V + \beta_4 \cdot C_L + \beta_5 \cdot D + \beta_6 \cdot T + \beta_7 \cdot FR + \varepsilon$, where ρ is the air density, T the Aircraft type and FR the Flight regime	Simulation-based using BADA 3.16 aircraft performance model Aircraft type: Six narrow-body types (e.g., A320 family)
Dalmau, Sun, and Prats [21]	Combination of simulation using Airbus PEP and analysis using ADS-B data from 4,139 real flights into EHAM. The study quantifies fuel inefficiencies caused by early descents, descents initiated before the optimal TOD computed by the onboard FMS.	Aircraft Dynamics (ODE System) $\frac{dv}{dt} = \frac{1}{m}\left[T(v,h) - D(v,h,m)\right] - g \sin\gamma$ $\frac{dh}{dt} = v \sin\gamma$ $\frac{ds}{dt} = v \cos\gamma$ $\frac{dm}{dt} = q(T,v,h)$ Early Descent: $\dot{h} = VS \cdot \left(\frac{\partial h_p}{\partial h}\right)^{-1} = f_1 VS$ $\dot{v} = \frac{\partial\theta}{\partial h} \cdot \left(\frac{\partial\theta}{\partial v}\right)^{-1} \cdot \left(\frac{\partial h_p}{\partial h}\right)^{-1} VS = f_2(\theta) f_1 VS$ Required Thrust During Early Descent: $T = D + mv\left[g + v f_2(\theta)\right] f_1 VS$	Simulated trajectories using Airbus PEP (Performance Engineering Program) for A320 4,139 real-world flights using ADS-B data in April 2018
Dekker [26]	Conceptual and simulation-based analysis of European airspace inefficiencies, focusing on the impact of route structure on flight time, fuel burn, and emissions. The study proposes a “Free Airspace” model to improve efficiency.	Scenarios: Trial 1: Full routing with SIDs, STARs, and waypoints Trial 2: Routing with SIDs and STARs only Trial 3: Direct routing (no SIDs, STARs, or waypoints)	Simulated flight data using SimBrief

Paper	**Approach**	**Calculations**	**Data Used**
Reynolds [8]	Analysis of lateral flight inefficiency using operational flight data across multiple regions. Quantification of extra distance flown compared to great circle routes, segmented by flight phase and identifies inefficiency sources such as standard routes, restricted airspace, and holding patterns.	Lateral Inefficiency Metrics: $IM_{Lateral} = \frac{D_{actual} - D_{optimal}}{D_{optimal}} \times 100$ Origin Terminal Area: $XD_{OriginTA} = (D_{TO} + D_{Turn} + D_{Depart}) - R_{TA}$ Enroute: $XD_{Enroute} = D_{Enroute\ actual} - D_{Enroute\ GC}$ Destination Terminal Area: $XD_{\text{DestTA}} = (D_{\text{Arrival}} + D_{\text{Hold}} + D_{\text{Downwind}} + D_{\text{Base}} + D_{\text{Final}}) - R_{\text{TA}}$	FDR data for European flights, ETMS radar track data for US flights, and MOZAIC in-flight measurements for African and intercontinental flights

References

[1] Kristine de Leon. *Numbers Show Flying Has Never Been Safer. Here's Why Experts Are Worried Anyway*. oregonlive. Apr. 16, 2024. URL: `https://www.oregonlive.com/business/2024/04/numbers-show-flying-has-never-been-safer-heres-why-experts-are-worried-anyway.html` (visited on 03/11/2026).

[2] Dabin Xue et al. "Low-Carbon Benefits of Aircraft Adopting Continuous Descent Operations". In: *Applied Energy* 383 (Apr. 2025), p. 125390. DOI: `10.1016/j.apenergy.2025.125390`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S0306261925001205` (visited on 06/18/2025).

[3] IATA. *Our Commitment to Fly Net Zero by 2050*. 2025. URL: `https://www.iata.org/en/programs/sustainability/flynetzero/` (visited on 08/03/2025).

[4] Ramazan Kursat Cecen. "Flight Regimes and Environmental Impact: A Linear Regression Analysis of Co2 Emissions for En-Route Air Traffic Operations". In: *International Journal of Aeronautical and Space Sciences* 26.4 (July 1, 2025), pp. 2058–2069. DOI: `10.1007/s42405-024-00860-z`. URL: `https://doi.org/10.1007/s42405-024-00860-z` (visited on 07/25/2025).

[5] *Reducing Emissions from Aviation - European Commission*. URL: `https://climate.ec.europa.eu/eu-action/transport-decarbonisation/reducing-emissions-aviation_en` (visited on 08/04/2025).

[6] K.A. ter Beek. "High Capacity Continuous Descent Operations". In: (2022). URL: `https://repository.tudelft.nl/record/uuid:7c57298e-23e9-408b-98a4-dbb2c63ed7ad` (visited on 07/02/2025).

[7] Xavier Olive et al. "Environmental Inefficiencies for Arrival Flights at European Airports". In: *PLOS ONE* 18.6 (June 23, 2023), e0287612. DOI: `10.1371/journal.pone.0287612`. URL: `https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0287612` (visited on 07/25/2025).

[8] Tom Reynolds. "Analysis of Lateral Flight Inefficiency in Global Air Traffic Management". In: *The 26th Congress of ICAS and 8th AIAA ATIO*. The 26th Congress of ICAS and 8th AIAA ATIO. Anchorage, Alaska: American Institute of Aeronautics and Astronautics, Sept. 14, 2008. DOI: `10.2514/6.2008-8865`. URL: `https://arc.aiaa.org/doi/10.2514/6.2008-8865` (visited on 07/29/2025).

[9] Saulo Da Silva. "Continuous Descent Operations (CDO)". ICAO SIP 2012 (Dakar). July 2012.

[10] Tom G. Reynolds. "Air Traffic Management Performance Assessment Using Flight Inefficiency Metrics". In: *Transport Policy*. Air Transportation and the Environment 34 (July 1, 2014), pp. 63–74. DOI: `10.1016/j.tranpol.2014.02.019`. URL: `https://www.sciencedirect.com/science/article/pii/S0967070X1400050X` (visited on 07/29/2025).

[11] Johannes Jaekel et al. "Air Traffic Control and Vertical Approach Efficiency at the Lower Airspace". In: *CEAS Aeronautical Journal* 16.2 (Apr. 1, 2025), pp. 591–611. DOI: `10.1007/s13272-024-00805-y`. URL: `https://doi.org/10.1007/s13272-024-00805-y` (visited on 07/25/2025).

[12] Sesar. *SESAR Joint Undertaking | MP 1 Executive Summary*. URL: `https://www.sesarju.eu/MasterPlan2025` (visited on 08/03/2025).

[13] ICAO. *Pbn Overview*. Pbn Overview. URL: `https://www.icao.int/safety/pbn/pbn-overview` (visited on 08/06/2025).

[14] SKYbrary. *Performance Based Navigation (PBN) | SKYbrary Aviation Safety*. URL: `https://skybrary.aero/articles/performance-based-navigation-pbn` (visited on 08/06/2025).

[15] ICAO. *PERFORMANCE-BASED NAVIGATION MANUAL*. ICAO.

[16] Jan Fiala et al. “Impact of Continuous Climb/Descent Procedure Implementation on ATCO Workload”. In: *2024 New Trends in Aviation Development (NTAD)*. 2024 New Trends in Aviation Development (NTAD). Nov. 2024, pp. 32–37. DOI: `10.1109/NTAD63796.2024.10850352`. URL: `https://ieeexplore.ieee.org/abstract/document/10850352` (visited on 06/27/2025).

[17] ICAO. *ANNEX 11 (2018): Air Traffic Services*. Place of publication not identified: ICAO, 2018.

[18] *Lecture_ADSB - AE4321-15 Air Traffic Management (2024/25 Q2)*. URL: `https://brightspace.tudelft.nl/d2l/le/content/679250/viewContent/3740081/View` (visited on 06/30/2025).

[19] Mithun Raghunandan. “Evaluating the Impact of Prediction Accuracy on Continuous Descent Operations: The Added Value of Trajectory Predictor Performance through Air-Ground Datalink”. In: (2024). URL: `https://repository.tudelft.nl/record/uuid:7cb83925-fdc2-49f6-96c2-560c40f61519` (visited on 06/25/2025).

[20] *Flight Management System: Lecture Slides - AE4302 Avionics and Operations (2024/25 Q2)*. URL: `https://brightspace.tudelft.nl/d2l/le/content/679230/viewContent/3739622/View` (visited on 08/06/2025).

[21] Ramon Dalmau et al. “Fuel Inefficiency Characterisation and Assessment Due to Early Execution of Top of Descents”. In: (2021). URL: `https://repository.tudelft.nl/record/uuid:6fbc7611-51a6-4508-add7-b3aeec390813` (visited on 07/02/2025).

[22] *Lecture_2_Airspaces - AE4321-15 Air Traffic Management (2024/25 Q2)*. URL: `https://brightspace.tudelft.nl/d2l/le/content/679250/viewContent/3740064/View` (visited on 06/27/2025).

[23] EUROCONTROL. *LSSIP 2021 THE NETHERLANDS LOCAL SINGLE SKY IMPLEMENTATION*. EUROCONTROL, 2021.

[24] LVNL. *eAIS Package for NETHERLANDS*. URL: `https://eaip.lvnl.nl/web/2025-07-24-AIRAC/html/index-en-GB.html` (visited on 08/06/2025).

[25] *Air Traffic Control and Management: Lecture Slides 2024 - AE4302 Avionics and Operations (2024/25 Q2)*. URL: `https://brightspace.tudelft.nl/d2l/le/content/679230/viewContent/3739659/View` (visited on 06/29/2025).

[26] Jonathan Dekker. “Introducing Free Airspace, a Way to Solve Europe’s Airspace Capacity Issues.” In: *Transportation Research Procedia*. 1st International Conference on Aviation Future: Challenge and Solution (AFCS 2020) 56 (Jan. 1, 2021), pp. 19–28. DOI: `10.1016/j.trpro.2021.09.003`. URL: `https://www.sciencedirect.com/science/article/pii/S235214652100630X` (visited on 06/30/2025).

[27] *Free Route Airspace at Maastricht UAC (FRA@MUAC) | EUROCONTROL*. Apr. 17, 2025. URL: `https://www.eurocontrol.int/service/free-route-airspace-maastricht-uac` (visited on 07/01/2025).

[28] SKYbrary. *Functional Airspace Block (FAB) | SKYbrary Aviation Safety*. Functional Airspace Block (FAB). URL: `https://skybrary.aero/articles/functional-airspace-block-fab` (visited on 08/06/2025).

[29] SKYbrary. *Trajectory Based Operations (TBO) | SKYbrary Aviation Safety*. Trajectory Based Operations (TBO). URL: `https://skybrary.aero/articles/trajectory-based-operations-tbo` (visited on 08/06/2025).

[30] EUROCONTROL. *Continuous Climb and Descent Operations (CCO / CDO) | EUROCONTROL*. Nov. 6, 2020. URL: `https://www.eurocontrol.int/concept/continuous-climb-and-descent-operations` (visited on 08/03/2025).

[31] ICAO. *Continuous Descent Operations (CDO) Manual*. ICAO, 2010.

[32] Joost Ellerbroek et al. “Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol”. In: (2018).

[33] H. Aksoy et al. “Effect of Vertical Profile Inefficiency during Descent on Fuel Burn, Emissions and Flight Time”. In: *The Aeronautical Journal* 122.1252 (June 2018), pp. 913–932. DOI: `10.1017/aer.2018.41`. URL: `https://www.cambridge.org/core/journals/aeronautical-journal/article/abs/effect-of-vertical-profile-inefficiency-during-descent-on-fuel-burn-emissions-and-flight-time/5FE3F0AF15D6511DEE5AF62B656D9D98` (visited on 07/25/2025).

[34] María del Pozo Domínguez et al. “Assessing the Environmental Impact of Continuous Descent Operations Based on Quick Access Recorder and Surveillance Data”. In: *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*. 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC). Madrid, Spain, Oct. 2023, pp. 1–9. DOI: `10.1109/DASC58513.2023.10311191`. URL: `https://ieeexplore.ieee.org/abstract/document/10311191` (visited on 06/26/2025).

[35] ATAG. *Waypoint 2050 2nd Edition: September 2021 (Full Report and Summary)*. 2021. URL: `https://atag.org/resources/waypoint-2050-2nd-edition-september-2021` (visited on 08/13/2025).

[36] Bart Bouwels. “Off-Idle Continuous Descent Operations at Schiphol Airport”. In: (2021). URL: `https://repository.tudelft.nl/record/uuid:fa55d141-ea6d-4bb9-b463-515742e55935` (visited on 08/19/2025).