Effects of increased trajectory predictability by ATS datalink on ATM operations in lower airspace

MSc Thesis

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by

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Preface

This thesis marks the completion of not only my master's degree in Aerospace Engineering at Delft University of Technology but also the end of my journey as a student. This began with my time in Aviation Studies at the Amsterdam University of Applied Sciences and continued through the bridging program at TU Delft. This research uses ADS-C datalink technology to improve operational efficiency and safety while improving air traffic control procedures in lower airspace.

I would like to sincerely thank several people who helped me along the way. First, I want to thank my company supervisor, Ferdinand Dijkstra, who gave me the opportunity to graduate at LVNL/KDC. Your constant support guided me in the right direction throughout my thesis. I would also like to thank my other supervisors, Jacco Hoekstra and Joost Ellerbroek, for their valuable feedback and suggestions, which improved the quality of my work.

Also, I am especially grateful to my friends and family, especially my parents and Marloes, who supported and encouraged me throughout this journey. Their kindness and belief in me helped me stay motivated, even during the toughest moments.

Finally, I would like to thank everyone at LVNL, iLabs and who contributed to this research in any way. I hope this thesis will add to the ongoing efforts to improve air traffic management and demonstrate the potential of ADS-C technology to optimize flight operations.

Thijs Scheffers

The Hague, November 2024

Contents

List of Tables

List of Figures

List of Abbreviations

ATS B2	Air Traffic Services B2.
4D	4-Dimensional.
AAA	Amsterdam Advanced Air traffic control system.
ACARS	Aircraft Communications and Reporting System.
ACC	Area Control Center.
ADS-B	Automatic Dependent Surveillance - Broadcast.
ADS-C	Automatic Dependent Surveillance - Contract.
AGDL	Air-to-Ground Datalink.
AMAN	Arrival Manager.
ANSP	Air Navigation Service Provider.
AOC	Aeronautical Operational Control.
APP	Approach Control.
ARINC	Aeronautical Radio Incorporated.
ASAS	Airborne Separation Assurance System.
ATC	Air Traffic Control.
ATCO	Air Traffic Controller.
ATM	Air Traffic Management.
ATN	Aeronautical Telecommunications Network.
ATS	Air Traffic Services.
ATSU	Air Traffic Services Unit.
CD&R	Conflict Detection & Resolution.
CPDLC	Controller-Pilot Datalink Communications.
CTA	Control Area.
CTR	Control Zone.
DARP	Dutch Airspace Redesign Program.
DMAN	Departure Manager.
DST	Decision Support Tool.
EPP	Extended Projected Profile.
EU	European Union.
EUROCAE	European Organisation for Civil Aviation Equipment.
EUROCONTROL	European Organisation for the Safety of Air Navigation.
FANS	Future Air Navigation Systems.
FDPS	Flight Data Processing Systems.
FIR	Flight Information Region.
FL	Flight Level.
FMS	Flight Management System.
FOM	Figure of Merit.
FPI	Fixed Projected Intent.
GATMOC	Global ATM Operation Concept.
IAF	Initial Approach Fix.
ICAO	International Civil Aviation Organisation.
IFR	Instrument Flight Rules.
ILS	Instrument Landing System.
IPI	Intermediate Projected Intent.
KPI	Key Performance Indicator.
LVNL	Luchtverkeersleiding Nederland.
MTCD	Medium Term Conflict Detection.
MUAC	Maastricht Upper Area Control Centre.
NM	Network Manager.

PBN	Performance Based Navigation.
RNP	Required Navigation Performance.
RTCA	Radio Technical Commission for Aeronautics.
SATCOM	Satellite Communications.
SID	Standard Instrument Departure.
STAR	Standard Terminal Arrival Route.
STCA	Short Term Conflict Alert.
SVFR	Special Visual Flight Rules.
TBO	Trajectory Based Operations.
TCP	Trajectory Change Point.
TM	Trajectory Management.
TMA	Terminal Manoeuvring Area.
TOA	Time Of Arrival.
ToD	Top of Descent.
TP	Trajectory Predictor.
UAC	Upper Airspace Control.
UTA	Upper Control Area.
VDL	VHF Datalink.
VFR	Visual Flight Rules.
VHF	Very High Frequency.

Part I
Scientific Paper

Effects of increased trajectory predictability by ATS datalink on ATM operations in lower airspace

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Abstract

This paper explores the impact of Automatic Dependent Surveillance - Contract (ADS-C) on air traffic control (ATC) procedures, focusing on operational efficiency and safety margins in lower airspace. Through 64 simulation configurations, the study evaluates how varying airspace density, separation buffer size, and vertical error in ADS-C data influence operational metrics, such as fuel burn, track miles, and flight time. The simulations utilize synthetic ADS-C data with a 100% equipage rate, providing insights into how ADS-C can be applied to manage intersecting flight trajectories. Results indicate that separation buffer size is the most influential factor. Smaller buffers lead to significant reductions in fuel burn, track miles, and flight time compared to the baseline, though this comes at the expense of increased conflict risks. Airspace density demonstrated trends where higher densities showed the greatest fuel savings but more conflicts, highlighting a trade-off between operational efficiency and safety. These findings support the role of ADS-C in increasing predictability and improving trajectory management, both of which are key to Trajectory-Based Operations (TBO). By improving the accuracy of aircraft intent and trajectory data, ADS-C can optimize flight paths and enable more efficient air traffic management. However, carefully considering separation buffers and airspace density is essential to balance efficiency with safety.

1 Introduction

In recent years, air traffic management (ATM) has advanced significantly with the development and enhancement of existing technologies to improve efficiency and safety. One of these advancements is the extension and refinement of Automatic Dependent Surveillance - Contract (ADS-C). ADS-C is a surveillance technology for tracking and monitoring aircraft during flight. Unlike traditional radar-based systems, ADS-C relies on onboard avionics to transmit position, altitude, speed, trajectory intent, and other valuable information to ground-based air traffic control (ATC) via air-to-ground datalinks. This enables more precise tracking and management of aircraft trajectories [1].

The latest generation of Air-to-Ground Datalink (AGDL), known as Air Traffic Services Baseline 2 (ATS B2) and recently developed by RTCA/EUROCAE [2], is currently being introduced into European airspace. As mandated by the European Union (EU), effective from 31 December 2027, aircraft receiving their first airworthiness certification on or after this date must be capable of downlinking and processing ADS-C Extended Projected Profile (EPP) data, which is part of ATS B2 [3]. An important element of this AGDL implementation is the availability of detailed trajectory information with flight intent. This application leads to improved predictability, as it allows for more accurate predictions of an aircraft's intentions and destination [4].

Within this context, ADS-C is an essential enabler for the Trajectory Based Operations (TBO) concept, which represents the future of ATM. Rather than focusing on managing aircraft within predefined airspace sectors, as is typical in traditional airspace-based operations, TBO emphasizes the management of individual aircraft trajectories. This approach aims to create an environment where the actual flight trajectory closely aligns with the user-preferred trajectory, reducing conflicts and improving efficiency. TBO uses detailed 4D trajectory data, which includes latitude, longitude, altitude, and time, to optimize flight paths and enhance decision-making processes for all stakeholders [5].

By transmitting detailed data about an aircraft's current and intended flight path at pre-defined time intervals, such as 1 minute or 5 minutes, ADS-C enhances the predictability and synchronization of trajectories. This data integration supports the key objectives of TBO, such as optimizing flight paths, reducing fuel burn, and minimizing environmental impact. Additionally, by providing detailed intent data, ADS-C enhances the capability of ATC systems to detect and resolve potential conflicts early, ensuring safe separation while optimizing trajectories. Implementing ATS B2 ADS-C is thus a significant step towards realizing the full potential of TBO in modernizing air traffic management and achieving safer, more efficient, and environmentally sustainable operations.

Since 30 May 2022, ATS B2 ADS-C has been operational at the Maastricht Upper Area Control Centre (MUAC). This early implementation highlights MUAC as one of the world's leading Air Navigation Service Providers (ANSPs) in adopting datalink technology for ATM [4]. Various studies have already focused on ADS-C, particularly the EPP [6, 7]. These studies primarily explored how ground-based prediction tools can utilize the EPP within the context of Trajectory Management (TM) to maximize its benefits. However, the application of the EPP to improve ATC procedures has not been addressed. A demonstration report by SESAR3 Joint Undertaking [8] examined these applications but focused mainly on the upper airspace. A key finding from this report was that Conflict Detection and Resolution (CD&R) can be improved using ADS-C EPP data. Research by Hao et al. [9] also focused on conflict detection within TBO contexts.

While MUAC has successfully integrated ADS-C into upper airspace operations, there is limited research on its applications to improve ATC procedures and its effectiveness in lower airspace. Lower airspace, managed by Approach Control (APP) and Area Control Center (ACC), extends from FL0 (Flight Level) to approximately FL245 [10]. This area presents significant challenges due to the complexities of high-density traffic, frequent altitude changes, and dynamic flight paths by ATC interventions.

This paper's main contribution is advancing ATM by utilizing ADS-C technology. Specifically, the research examines how ADS-C can aid in situations where inbound and outbound traffic intersect — an issue identified as critical in the Dutch Airspace Redesign Program (DARP). The study aims to provide new insights into the practical applications of ADS-C, particularly in improving ATC procedures within lower airspace, thereby offering effective solutions for managing trajectory conflicts and enhancing operational efficiency and safety.

The remainder of this paper is structured as follows: Section 2 provides the background on TBO and datalink technology. Section 3 details the methods used in this study. Section 4 describes the experimental setup. Section 5 presents the results of the simulations and analysis. Finally, Section 6 and Section 7 discuss the implications of these findings and a conclusion to the paper.

2 Background

The aviation industry continuously seeks advancements to improve the efficiency, safety, and sustainability of air traffic management (ATM) systems. In Europe, initiatives like the Single European Sky ATM Masterplan aim to address these goals by adopting innovative operational concepts and technologies.

2.1 Trajectory Based Operations (TBO)

TBO is a crucial concept in modern ATM, designed to reach the performance targets set by the Single European Sky ATM Masterplan. The International Civil Aviation Organisation (ICAO) introduced the Global ATM Operation Concept (GATMOC) [11], which aims to create an airspace where operations are more predictable and efficient. Central to this is real-time data transmission from aircraft, enabling ATC to make more informed decisions regarding flight paths, conflict resolution, and airspace capacity.

According to Bronsvoort et al. [6], TBO centers around two elements:

1. **Performance Based navigation (PBN)**: This is a modern concept for defining and implementing navigation in aviation that allows for the precise and efficient use of airspace and air traffic routes. It differs from traditional navigation, which relies heavily on ground-based navigation aids using satellite systems and onboard navigation technology. PBN enables aircraft to fly a specific path more accurately, flexibly, and efficiently.
2. **Trajectory Management (TM)**: TM is the systematic process of planning, monitoring, and adjusting the flight paths of aircraft to optimize airspace capacity and ensure safe, efficient operations. It involves coordinating the trajectories of individual aircraft to prevent conflicts and minimize delays, taking into account real-time factors such as weather conditions, air traffic density, and airspace restrictions. By managing trajectories proactively, ATC can facilitate smoother flight paths, reduce fuel consumption, and enhance overall operational efficiency. Additionally, TM enables a shared understanding between pilots and controllers of an aircraft's intended route, allowing for better synchronization between airborne and ground-based systems. This differs from conventional ATC, focusing on proactive, real-time adjustments to optimize aircraft trajectories. In contrast, traditional ATC often relies on reactive measures to resolve conflicts and manage separations as they arise.

2.2 Datalink Technology

In aviation, datalink technology is crucial in modernizing air-ground communication, marking a significant shift away from traditional voice-based methods. The limitations of voice communication, such as frequency congestion and communication errors, highlight the need for more reliable and efficient methods. Consequently, digital communication methods were developed, facilitating direct communication between aircraft and ground stations, including those operated by Air Navigation Service Providers (ANSPs) and airlines. 'Datalink' broadly encompasses three main components: applications, infrastructure, and standards [12].

Datalink applications, such as ADS-C, Automatic Dependent Surveillance - Broadcast (ADS-B), and Controller-Pilot Data Link Communications (CPDLC), facilitate the exchange of critical flight information between aircraft and ground systems, supporting air traffic management operations. ADS-C automates periodic or event-triggered reports, such as position updates, waypoint deviations, and altitude changes, which are interesting for controllers and their decision-support tools. In contrast, ADS-B continuously broadcasts real-time position information to both air traffic controllers and nearby aircraft, enhancing situational awareness. CPDLC offers predefined and free-text messaging, supplementing or replacing traditional Very High Frequency (VHF) communications.

The supporting infrastructure includes onboard avionics, ANSP interfaces, and underlying networks like Aircraft Communication and Reporting System (ACARS) and Aeronautical Telecommunication Network (ATN). ACARS, developed by Aeronautical Radio Incorporated (ARINC), enables global digital messaging between aircraft and ground systems. ATN, primarily developed in Europe, offers enhanced transmission speed and robustness compared to ACARS. Key sub-networks include VHF Digital Link (VDL) Mode 2 for VHF communications and satellite communications (SATCOM) for areas where VDL is impractical.

International standards ensure interoperability and consistency across regions and aircraft types. Three primary standards have been developed, each building on the previous one. These standards include FANS 1/A, introduced in the early 1990s to enable CPDLC and ADS-C; the ATS B1 standard, which supports only CPDLC; and the latest ATS B2 standard, which fully supports both CPDLC and ADS-C with an expanded set of messages and datasets.

2.3 Automatic Dependent Surveillance (ADS)

ADS is a technology used in modern ATM to track and monitor aircraft more efficiently than traditional radar systems. It relies on aircraft to automatically transmit data regarding their position, velocity, and other flight parameters to ground stations, such as ATC or other aircraft. The system is "automatic" because it requires no pilot input or interrogation from ground-based radar. It is "dependent" on the aircraft's onboard navigation systems, such as GPS, to provide accurate positional information. ADS is divided into two main types: ADS-B and ADS-C. Table 1 presents the key differences between these systems.

ADS-B ADS-B is a surveillance technology used to track aircraft positions with high accuracy. It continuously broadcasts an aircraft's position, velocity, and other flight information to ground stations and nearby aircraft in real time for enhanced situational awareness. The primary components of ADS-B include:

- **ADS-B Out:** Automatically transmits GPS-based position, altitude, speed, and heading information to air traffic controllers and other ADS-B-equipped aircraft.
- **ADS-B In:** Allows an aircraft to receive similar information from other aircraft and ground stations.

As this research focuses on the potential applications of ADS-C rather than CPDLC and ADS-B, the concept of ADS-C will be explored in more detail in the following section.

2.4 ADS-C Datalink

ADS-C uses several aircraft onboard systems to autonomously gather and transmit data such as location, altitude, speed, intent, and weather conditions. This information is compiled into reports and transmitted to an Air Traffic Services Unit (ATSU) or Airline Operations Center (AOC) ground system. ADS-C reports are generated based on contracts established by the ground system, specifying the required information and the conditions for report transmission. While some data is always included, others are transmitted only when requested in the ADS contract [1]. A schematic overview of the operational context of ADS-C is given in Figure 1.

Table 1: *Comparison of ADS-B and ADS-C*

Characteristic	ADS-B	ADS-C
Communication Type	Broadcast	Contract-based
Data Transmission	Sent to ground stations and nearby aircraft in real-time	Sent only to ground stations based on contracts
Usage Area	Primarily in areas with ground infrastructure (e.g., continental airspace)	Remote and oceanic areas with limited or no radar coverage
Data Frequency	Continuous real-time updates	Periodic (or event-triggered) updates based on contracts
Primary Communication Medium	Mode S transponder	Satellite communications

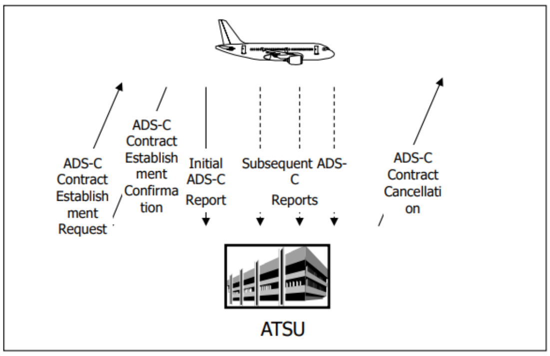

Figure 1: *ADS-C operational context [2]*

Table 2: *Different ADS-C groups FANS 1/A and ATS B2*

FANS 1/A	ATS B2
Basic group	Basic group
Flight identification	Air vector
Air reference	Ground vector
Airframe identification	Projected profile
Meteorological	Meteorological
Predicted route	RTA status
Fixed projected intent	TOA range
Intermediate projected intent	Speed schedule profile
	Extended projected profile

There are three basic types of ADS-C contracts:

- **Periodic Contracts:** Define the reporting frequency at which the Flight Management System (FMS) must transmit ADS-C reports to the ground system. Only one periodic contract can be established between a particular ground system and a specific aircraft at any given moment.
- **Event Contracts:** Triggered by specific events, such as lateral deviations or waypoint changes. Only one event contract between a ground system and an aircraft can be established. However, this contract can contain multiple events.
- **Demand Contracts:** Single requests for an ADS-C report for specific information, often used to refresh data. Multiple demand contracts can be established consecutively.

As previously discussed, two standards support ADS-C: FANS 1/A and ATS B2. The latter provides more detailed information than FANS ADS-C, but they are related. Table 2 presents the difference in groups between the two standards.

The most important groups for this research are the Intermediate Projected Intent (IPI) from FANS 1/A and the Extended Projected Profile (EPP) from ATS B2. The IPI group includes up to 10 Trajectory Change Points (TCPs) between the aircraft's current position and the fixed projected point in the FPI group. These points, generated by the FMS, such as the Top of Descent (ToD), represent planned speed, altitude, or route changes and may not correspond to any specific waypoint in the flight plan [1].

The EPP enhances the IPI group in FANS by providing a detailed 4D flight trajectory, including lateral and vertical TCPs, gross mass, and trajectory intent status. An EPP report can include up to 128 TCPs, and each point is described with position, altitude, waypoint name, estimated speed, time, and any constraints. Additionally, it includes lateral points like Fly-by or Fixed Radius Transitions, Fly-over Transitions, and Vertical points such as Top of Descent, Start of Descent, and Start/End of Speed Change, which are crucial for this research [2]. These two groups' differences are shown in Appendix B.

2.5 Dutch Airspace Redesign Program (DARP)

The DARP is a collaborative initiative involving the Ministry of Infrastructure and Water Management, the Ministry of Defence, the Royal Netherlands Air Force, LVNL, and MUAC. The program aims to improve Dutch airspace's efficiency, safety, and environmental sustainability to meet future demands [13]. A key focus of DARP is integrating civilian and military airspace to allow more flexible and efficient operations. Additionally, DARP aims to support the growing use of unmanned aerial vehicles (UAVs) and improve flight routing to reduce CO2 emissions and noise pollution. This research aligns with DARP's objectives by exploring the potential of ADS-C to enhance the predictability and efficiency of air traffic in lower airspace.

2.6 Separation minima

The primary objective of ATC is safety, which is achieved by maintaining safe separation between aircraft in controlled airspace at all times. This separation acts as a preventive buffer to avoid collisions and includes vertical, horizontal, and wake turbulence separation, with different minima applicable during various phases of flight.

Vertical separation minima (VSM) requires a minimum of 300 meters (1000 feet) below FL290 and 600 meters (2000 feet) above. With Reduced Vertical Separation Minima (RVSM) above FL290, the separation is reduced to 300 meters (1000 feet) up to FL410. When using ATS surveillance systems like radar or Automatic Dependent Surveillance - Broadcast (ADS-B), the minimum horizontal separation is typically 5 nautical miles (NM). This can be reduced to 3 NM in areas with enhanced system capabilities, such as the Terminal Maneuvering Area (TMA), and even to 2.5 NM under specific conditions near the runway threshold.

When two aircraft are on the same track, separation serves two purposes: preventing collisions and mitigating the risk of wake turbulence. Wake turbulence, created by a heavier aircraft and encountered by a lighter one following too closely, can be highly dangerous and potentially lead to a loss of control. To mitigate this risk, additional separation based on the aircraft's Maximum Take-Off Mass (MTOM) is required [14].

Wake RECAT (Wake Turbulence Re-categorization) enhances airport efficiency and capacity by refining aircraft wake turbulence categorization. Unlike the traditional method, Wake RECAT considers both mass and aerodynamic characteristics, allowing for closer, safer spacing between certain aircraft types, thus increasing capacity and reducing delays without compromising safety [15].

3 Methodology

This research uses a simulation-based, quantitative approach to evaluate how increased predictability through ADS-C datalink technology impacts air traffic control (ATC) procedures in lower airspace. A comparative analysis is performed between a baseline simulation with no ADS-C and multiple simulations incorporating ADS-C, allowing for an assessment of operational efficiency and safety improvements.

3.1 Research design

The methodology centers on simulating air traffic at Amsterdam Airport Schiphol using pre-defined scenario files from the Dutch Airspace Redesign Program (DARP). These files include defined routes for both inbound and outbound aircraft. Four routes are utilized for inbound traffic. As runways 36C and 36L operate independently, two routes are assigned to departures from runway 36L, and six routes are designated for departures from runway 36C. The study specifically focuses on the impact of ADS-C on intersecting trajectories between inbound and outbound aircraft, a critical situation in the DARP, where such intersecting routes increase the workload for air traffic controllers.

Due to the limited availability of actual ADS-C data, synthetic data were used to simulate real-world ADS-C messages. Furthermore, this study assumes a 100% equipage rate of ADS-C datalink for all aircraft. This hypothetical setup allows for exploring the optimal potential impacts and benefits of ADS-C technology on air traffic procedures in lower airspace without the variable of partial equipage rates. This assumption is critical for focusing the research on the capabilities of ADS-C datalink technology itself rather than the current or future reality of mixed equipage levels.

3.2 Independent variables

The independent variables were systematically adjusted across the experimental runs to assess their effects on the dependent variables. These variables include:

Airspace density This variable quantifies the number of arriving and departing aircraft per runway within a specific time frame, such as an hour. Scenarios are constructed with four density levels, minimal, low, medium, and high, designed to reflect varying traffic conditions at Schiphol Airport. The minimal category was added to assess whether there is any non-linearity in the results due to variations in airspace density.

- **Arrivals:**
  - Minimal (17 aircraft per hour)
  - Low (30 aircraft per hour)
  - Medium (34 aircraft per hour)
  - High (38 aircraft per hour)
- **Departures:**
  - Minimal (17 aircraft per hour)
  - Low (32 aircraft per hour)
  - Medium (36 aircraft per hour)
  - High (40 aircraft per hour)

Minimal Separation Buffer This represents the 'mental buffer' set by controllers to determine potential conflict situations. Additionally, it is the minimum allowable altitude distance between aircraft that is necessary for the optimization of their trajectories. Four levels of separation buffer are used - minimal, low, medium, and high - to explore how changes in buffer size affect the optimization process and how closely aircraft can be managed while maintaining safe separation. These levels were chosen to simulate a more conservative approach (4000 ft) to a more aggressive one (1000 ft).

- Minimal (1000 ft)
- Low (2000 ft)
- Medium (3000 ft)
- High (4000 ft)

Vertical error component Since no clearly defined and reliable source for vertical error in ADS-C data is currently available, an estimation approach was chosen. These error values were determined based on expert judgment, suggesting that the vertical error at FL100 during descent from cruise altitude could fall within the selected range. The same logic applies to the climb. If future research provides more accurate data on ADS-C vertical errors, it will be possible to identify which of these scenarios most closely aligns with the actual error level. The study introduces four levels of vertical error, represented as one Standard Deviation (SD) value — zero, low, medium, and high — to explore how these deviations impact trajectory optimization and conflict detection.

- Zero error (0 ft)
- Low error (100 ft)
- Medium error (200 ft)
- High error (500 ft)

3.3 Dependent variables

The following dependent variables are measured to assess the outcomes of different manipulations of the independent variables. They fall into three main categories:

- **Operational efficiency:** Measured by the metrics: fuel burn, track miles, work done, total flight time, and horizontal flight time.
- **Safety margins:** Measured by adherence to separation minima and the occurrence of potential conflict situations, i.e., whether aircraft maintain the minimal separation buffer.
- **Optimized trajectories:** The number of times trajectories are optimized or not optimized reflects the impact of ADS-C data on flight path adjustments. Additionally, total potential conflicts and any constraining actions are also recorded.

3.4 Simulation Framework

The simulations for this study are conducted using the BlueSky ATM simulator. This open-source air traffic management program allows detailed modeling of aircraft trajectories and airspace dynamics [16]. BlueSky provides a flexible platform for replicating complex air traffic environments, making it well-suited for this research, which focuses on the interaction of intersecting inbound and outbound flight trajectories at Amsterdam Airport Schiphol.

A custom sequence algorithm was developed to handle aircraft scheduling and spacing based on different airspace densities. This system ensures that aircraft separation is maintained according to predefined rules, which vary depending on traffic conditions, such as airspace density (minimal, low, medium, or high). The sequence is calculated for arrivals by estimating travel times from the spawning points to the runway, while departures are assigned intervals based on Wake-RECAT separation guidelines.

3.5 Statistical Analysis

A series of statistical tests was conducted to evaluate the simulation results. These tests compared the outcomes of the differences between the baseline and grouped simulations, organized by each independent variable. For example, simulations were grouped by airspace density levels (minimal, low, etc.), allowing for comparisons across these groups for all dependent variables.

Shapiro-Wilk test To determine the appropriate statistical tests, the datasets from the simulation and baseline runs were first analyzed for normality using the Shapiro-Wilk test. This test evaluates whether the data are normally distributed by comparing the sample distribution to a perfectly normal distribution. It calculates a W-statistic, where values closer to 1 indicate normality. If the p-value from the test is below a predefined significance level (e.g., 0.05), the null hypothesis of normality is rejected, meaning the data are not normally distributed. It was applied to all dependent variables to assess whether the data followed a normal distribution.

Kruskal-Wallis Test Due to the non-normal distribution of the datasets, as indicated by the Shapiro-Wilk test, non-parametric tests were chosen for analysis. Since the independent variables have multiple groups, the Kruskal-Wallis test was used. This test is appropriate when comparing more than two independent groups and evaluates whether there is a statistically significant difference in the distribution of values across the groups. It does so by ranking all values from all groups together and then comparing the ranks between the groups, producing an H-statistic. This statistic is used to compute a p-value, which helps to determine whether at least one of the groups significantly differs from the others.

The significance (alpha) threshold was set at 0.05, a commonly used level in hypothesis testing. If the p-value was less than 0.05, the null hypothesis (H_0) was rejected, meaning that there was sufficient evidence to suggest that at least one group differed significantly. If a significant result was found, post-hoc analysis was performed in some cases using Dunn's test to determine which groups differed.

The research hypothesis tested whether the independent variables — airspace density, separation buffer, and vertical ADS-C error - significantly affect the dependent variables. The hypotheses are grouped into these three categories and are formulated as follows:

Hypothesis on Airspace Density

- **Research Hypothesis** H_1: Increasing airspace density will negatively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly reduces the frequency of optimizations but increases the occurrence of conflict situations.

Hypothesis on Separation Buffer

- **Research Hypothesis** H_1: Increasing separation buffer will negatively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly reduces the frequency of optimizations and the occurrence of conflict situations.

Hypothesis on vertical Error in ADS-C data

- **Research Hypothesis** H_1: Increasing the vertical error in ADS-C data will positively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly increases the frequency of optimizations and the occurrence of conflict situations.

Correlation Analysis A correlation analysis was conducted to explore potential relationships between dependent variables. Spearman's rank correlation coefficient was used to account for the non-normal distribution of the data. This non-parametric method measures the strength and direction of the association between two variables by ranking the data and calculating a correlation coefficient. Values range from -1 to 1, where values close to 1 indicate a strong positive correlation, and values near -1 indicate a strong negative correlation. Scatter plots were also generated to visualize these relationships, providing a clear view of trends and associations between the variables.

4 Experimental Setup

This section outlines the technical aspects of the experiment, including an explanation of the developed tool, pre-processing steps, and the configuration of multiple experimental runs to assess the impact of ADS-C data on intersecting trajectories in air traffic management. As discussed in the previous section, the open-source ATM simulator BlueSky was used. Scenario files included specific commands to spawn aircraft, assign waypoints, and manage takeoff and landing sequences.

A total of 64 experimental configurations were developed, each combining different levels of the independent variables, resulting in a complete factorial design. Each configuration was executed five times to account for variability in the results, introduced through changes in aircraft types, sequencing, and vertical error, as will be explained in Section 4.2. This approach resulted in 320 simulation runs, allowing for a thorough assessment of variability and performance.

The research follows an experimental test matrix, analyzing the differences between the baseline run (without ADS-C data) and the simulation runs. Appendix A presents the total experimental test matrix. The simulations focus solely on departures and arrivals at Amsterdam Airport Schiphol, with a total scenario time of 5.5 hours. To ensure that only the period of total traffic density is measured, a ramp-up and ramp-down phase of both 45 minutes is incorporated, resulting in an actual logging period of 4 hours. During this period, only complete flights are considered: aircraft that appeared on radar after 00:45:00 and were deleted from radar before 04:45:00 are included in the analysis.

4.1 Tool for Managing Intersecting Trajectories

A custom tool is developed to manage and optimize aircraft trajectories when inbound and outbound flights intersect. It assumes a 100% equipage rate of ADS-C datalink, enabling an exploration of the full potential of ADS-C technology in managing intersecting flight paths. The tool dynamically identifies potential conflict situations (i.e., intersection points) between inbound aircraft landing on runway 36R and outbound aircraft departing from runways 36L and 36C. If no intersection is detected with any aircraft currently on the radar, the trajectory is fully optimized without further constraints.

In cases where an intersection is identified, the tool calculates a so-called 'cylinder' around this intersection point with the necessary separation distances. A 5 NM lateral and 1000 ft vertical separation buffer (or 3 NM lateral separation within the TMA) is applied to ensure safe operations. The tool then leverages ADS-C data to predict the altitude of each aircraft at a distance of 5 or 3 NM from the intersection, using linear interpolation. Since altitude, speed, and heading changes are logged, the distances between these points are relatively small, allowing for a linear relationship assumption. This prediction method is chosen for its simplicity and effectiveness in estimating altitude changes over these short distances.

If the absolute altitude difference between aircraft at the calculated coordinates exceeds the predefined separation buffer, trajectory optimization is possible. This threshold corresponds to the four levels of the independent variable, separation buffer. Before continuing with the optimization, the tool checks if the optimized trajectory would cause a potential conflict with another aircraft. If a conflict is found, the optimization is not performed. If no conflict is found, the tool proceeds with the optimization. The optimization involves issuing a 'direct' command to the Flight Information Region (FIR) boundary for outbound aircraft or adjusting waypoint altitude constraints for inbound aircraft, allowing them to fly unconstrained until they intercept the Instrument Landing System (ILS).

If the absolute altitude difference at the calculated coordinates is smaller than the threshold, the tool determines which aircraft has the higher altitude at the intersection. The trajectory of the lower one is constrained to prevent a potential conflict. However, if the lower aircraft is an inbound flight and its trajectory has already been optimized, constraining this path is not ideal, as the aircraft might lack sufficient energy to descend to meet the altitude constraint. In such cases, the outbound flight is diverted from its route to avoid the potential conflict. The diversion allows the outbound aircraft more time to climb and reach a higher altitude around the intersection point.

4.2 Creating the simulation files

As previously mentioned, the initial routes from the DARP were used in the simulation files. A fixed alternating pattern for route assignment was implemented to account for the different number of aircraft in the scenario files due to varying airspace densities. For inbound aircraft, four routes were assigned in a repeating sequence: routes 1, 2, 3, and 4. A similar pattern was applied to runway 36C, which had six routes, assigned in sequence from routes 1 through 6 and then repeated. For runway 36L, with two available routes, assignments alternated between routes 1 and 2.

A minor alteration was made to the pre-defined outbound routes to simulate more realistic operations. In the original scenario files, aircraft take off immediately from the runway. However, in this study, a simulated taxi time was added to account for the time the aircraft takes to reach the runway from the gate. This adjustment reflects real-world operations, where ADS-C data is available while the aircraft is taxiing. The simulated taxi time varies based on the runway: for runway 36L, the taxi time is approximately 17 minutes, while for runway 36C, it is around 12 minutes. These values were incorporated into the simulation files to reflect actual taxiing conditions at Schiphol Airport better.

Additionally, variability in aircraft type was adjusted to reflect the varying characteristics of aircraft operating at Schiphol, such as their climb, descent, and wake turbulence profiles. The distribution of aircraft types was based on expert judgment and real-world traffic at Schiphol, where approximately 17% of aircraft are classified as heavy types during the morning peak, dropping to 8% in the evening peak. The remaining aircraft were categorized as medium, while light aircraft were excluded from this research, as they represented a minimal percentage of the traffic in the original DARP files. Also, they are largely excluded from the usual traffic operations at Schiphol, reflecting their small presence in real-world traffic.

Moreover, since this research used fixed routes from the DARP files, custom sequences for arriving and departing aircraft were developed to ensure safe and realistic operations. These sequences were adjusted based on the independent variable of airspace density, forming the baseline for assessing the impact of ADS-C technology. For the arrival sequence, the flight time required for each inbound aircraft to travel from its spawning point to the runway was determined. Aircraft were assigned timestamps with varying separation intervals depending on the applicable airspace density and flight time. Departures were sequenced according to the Wake-RECAT guidelines, with a default separation interval based on airspace density and adjustments for different aircraft categories to account for wake turbulence characteristics.

The sequence of arriving and departing aircraft was slightly adjusted in each run to introduce additional variability into the scenarios. A 30-second standard deviation was applied to introduce randomness in the timing and spacing between aircraft.

4.3 Synthetic ADS-C data

As previously mentioned, this research used synthetic ADS-C data. To generate this data, a baseline simulation run for each density was conducted without the optimization tool. For each change in altitude, heading, or speed, a new Trajectory Change Point (TCP) was logged. This allows the data to be used in the simulations as real-time ADS-C reports generated by the Flight Management System (FMS). A new report is generated every minute, resulting in a periodic ADS-C contract with a frequency of 1 minute. Each report updates the aircraft's current location and the predictive TCPs at one-minute intervals. However, since these reports would reflect the actual trajectory the aircraft has flown, a vertical error component was introduced as an independent variable to add a layer of realism.

The vertical error was modeled as an error rate, which introduces a bit of noise into the predicted altitudes. This error rate is determined by dividing the vertical error component, which is the independent variable, by the difference between the highest initial altitude of the simulation scenarios (FL340) and FL100, as shown in Equation 1. The reason for this method is explained in Section 3.2. The error rate remains constant while generating the ADS-C reports for an individual flight.

$$Error\ rate = \frac{Error\ level}{(FL340 - FL100)} \tag{1}$$

Once the error rate is calculated, the actual error for each TCP is determined through an iterative process. For each TCP in the ADS-C report, acquired by the baseline run just described, the altitude difference between the current and predicted altitude at that point is calculated. This altitude difference is multiplied by the error rate to produce a one standard deviation (SD) error value. To introduce randomness, a normal probability density function (PDF) is applied to this one-SD error value, with the PDF centered around a mean of zero. This process adds a 'noise' factor to the predicted altitude, resulting in a predicted altitude that includes an error factor.

This method ensures that as the altitude difference between the current and predicted altitudes becomes larger, i.e., the predicted altitude is further away in the future, the probability of a larger error value from the PDF increases, leading to greater predictive errors.

5 Results

This section presents the results of 64 simulation configurations designed to assess the impact of varying airspace density, separation buffers, and vertical error in ADS-C data on operational efficiency and safety margins. Additionally, four baseline simulations were conducted for each density level without using the optimization tool to provide a reference point. Metrics described in the previous section were measured against their respective baseline to evaluate the system's performance under different conditions. The output data was normalized based on the total number of aircraft to ensure a fair comparison. Finally, the larger the negative difference, the more desirable the results are compared to the baseline. This relationship is expressed in Equation 2.

$$\Delta = \left(\frac{\text{Sim Value}}{\text{Total Ac in Sim}}\right) - \left(\frac{\text{Baseline Value}}{\text{Total Ac in Baseline}}\right) \tag{2}$$

5.1 Fuel Burn

Since fuel burn is the leading metric in this research, the effects of all three independent variables on fuel burn are discussed in more detail.

Impact of Airspace Density Figure 2 presents the fuel burn delta per aircraft across the four levels of airspace density. Using the Kruskal-Wallis tests, statistical analysis on the effect of airspace density on fuel burn is not significant (KW-statistic = 6.4821, p = 0.09). Therefore, we do not have sufficient evidence to reject the null hypothesis and cannot conclude that airspace density significantly impacts the difference in fuel burn compared to the baseline. However, the relatively low p-value suggests that the variation might still be meaningful and could warrant further investigation with a larger sample size or more sensitive analysis.

The plot indicates that the median values for minimal, low, and high densities are close, with high density showing the lowest median value. Additionally, the minimal density scenario has the smallest interquartile range (IQR) but the largest overall spread. The medium-density scenario has the worst median reduction, indicating that the simulations generally result in fewer fuel savings under these conditions than the minimal, low, and high-density scenarios.

However, it is important to note that the optimization tool used in the simulations does not necessarily solve actual conflicts but instead tries to prevent potential conflicts utilizing ADS-C data. If an actual conflict occurs, the tool or the aircraft does not take further action. In real-life operations, this could result in optimizations occurring less frequently in a high-density scenario, reducing fuel efficiency overall. This explains why, despite similar fuel savings, the minimal-density scenario may be considered better. It performs similarly to the high-density scenario regarding median fuel efficiency but with far fewer conflicts, thus providing better safety and more consistent optimization opportunities without the same level of risk. The loss of separation frequency normalized per aircraft is shown in Appendix C.1.

Effect of Separation Buffer The following variable discussed is the separation buffer, which is critical in determining how aggressive or conservative the air traffic control strategy is. Figure 3 illustrates the difference in fuel burn compared to the baseline, normalized per aircraft and grouped by the four buffer levels. A Kruskal-Wallis test on the effect of separation buffer on the fuel burn indicates that this effect is statistically significant (KW-statistic = 40.3186, p = 0.00). Therefore, there is enough evidence to reject the null hypothesis, confirming that separation buffer size significantly affects fuel burn. A post-hoc analysis with Bonferroni correction (e.g., Dunn's test) was performed to determine which specific buffer levels are responsible for these differences.

The results of Dunn's test indicate statistically significant differences between several buffer levels. Notably, minimal buffer showed a substantial difference in fuel burn compared to high (p = 0.00) and medium (p = 0.0014), while low buffers also exhibited a significant difference when compared to high buffer (p = 0.00). However, comparisons between medium and high and low and medium did not yield statistically significant results. These results suggest that the minimal and low separation buffers substantially impact fuel burn compared to higher separation buffer levels.

The plot illustrates that the minimal buffer scenario has the highest median fuel savings and the lowest overall spread and IQR, generally performing the best. A single outlier suggests a case of reduced efficiency, though it is not significant enough to affect the overall interpretation. The plot shows a clear trend where the median fuel savings decrease as the separation buffer increases while the overall spread and IQR increase. This is expected, as larger buffers simulate a more conservative approach by controllers, limiting the extent to which trajectory optimizations can be applied.

Additionally, both the overall spread and the IQR increase as the buffer size grows, indicating greater variability in fuel savings for higher buffer scenarios. This suggests that while higher buffer scenarios introduce more variability in performance, minimal buffer scenarios lead to more consistent results with higher fuel savings. This increased variability for the medium and high buffers reflects that, in some cases, the optimization can still yield reasonable improvements. Still, in others, it leads to significantly less fuel savings, likely due to the restrictions imposed by larger separation buffers.

Effect of Vertical Error in ADS-C Data The introduction of synthetic vertical errors into ADS-C data provided insight into how varying levels of vertical inaccuracy affected system performance. Figure 4, grouped by vertical error, presents the fuel burn delta with the baseline per aircraft. Statistical analysis using Kruskal-Wallis showed insufficient evidence to reject the null hypothesis. It could not be concluded that vertical error significantly impacts the difference in fuel burn compared to the baseline. (KW-statistic = 2.7826, p = 0.43).

Interestingly, there is an increasing trend in median fuel savings and a decreasing trend of overall spread as the vertical error increases, with the zero error scenario having the lowest median fuel savings and the high error scenario showing the highest.

This increasing trend in fuel savings with increasing error might initially seem counterintuitive. However, it could be explained by edge cases where the altitude differences between aircraft are close to the separation buffer. As vertical error increases, these altitude differences may exceed the buffer, leading to more opportunities for trajectory optimizations. This would result in greater fuel savings because the tool can optimize more aggressively when separation limits are breached by the error margin, particularly in high error cases.

5.2 Track miles

The difference in distance flown, or track miles, respective to the baseline, was analyzed to assess the impact of the independent variables. The results from the Kruskal-Wallis tests indicate that airspace density and vertical error do not have a statistically significant effect on track miles ($p > 0.05$). Given the lack of evidence to reject the null hypothesis for these variables, they will not be discussed explicitly. However, the results show that the separation buffer has a statistically significant effect on track miles. Therefore, the impact of separation buffers on track miles will be explored in more detail.

Effect of Separation Buffer Figure 5 illustrates the difference in track miles between the baseline and the simulations, grouped by separation buffer size. As previously mentioned, the separation buffer has a significant effect on track miles, as determined by the Kruskal-Wallis significance test (KW-statistic = 50.0942, p = 0.00). This indicates sufficient evidence to reject the null hypothesis, demonstrating that changes in separation buffer size lead to significant variations in track miles. However, similar to the fuel burn, to determine which specific levels cause these differences, a post-hoc analysis with Bonferroni

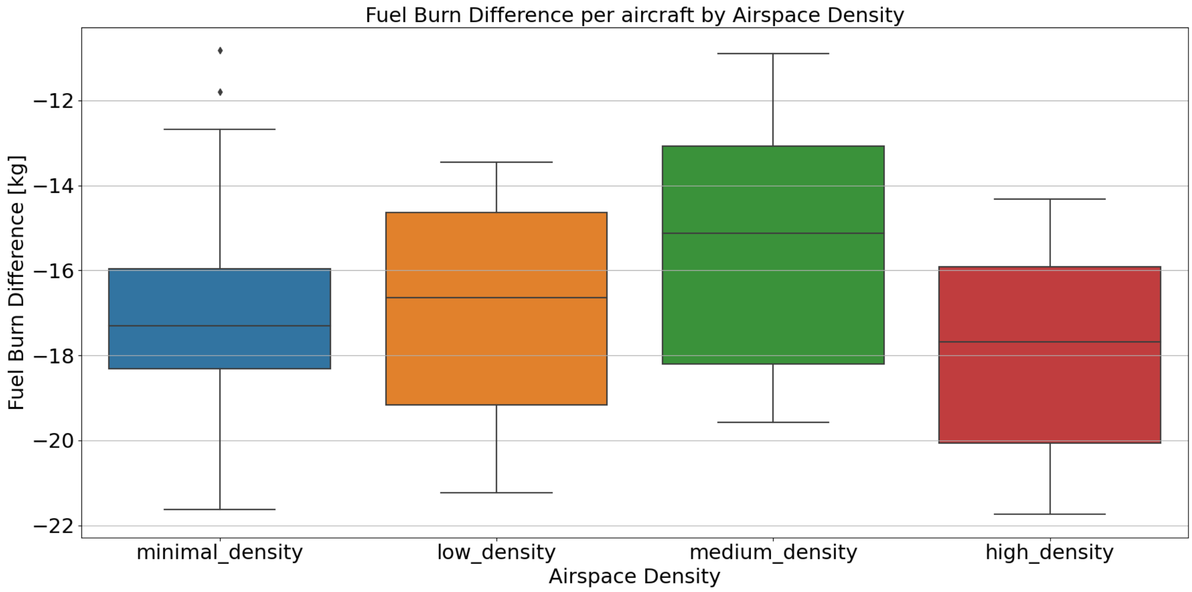

Figure 2: *Fuel Burn difference with baseline per aircraft grouped by density*

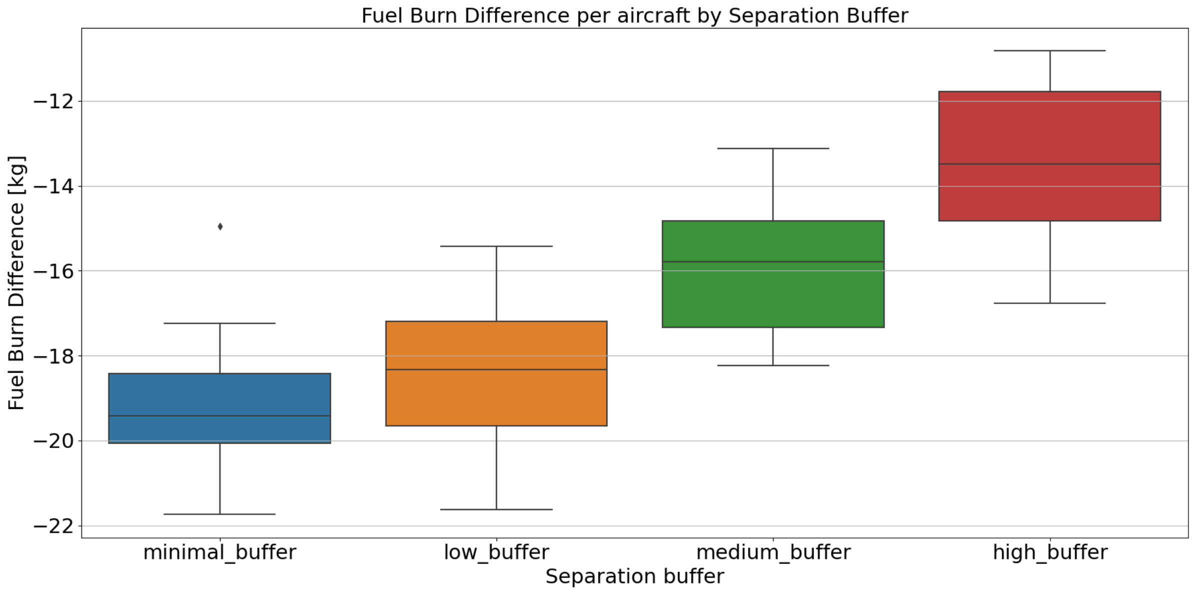

Figure 3: *Fuel Burn difference with baseline per aircraft grouped by buffer*

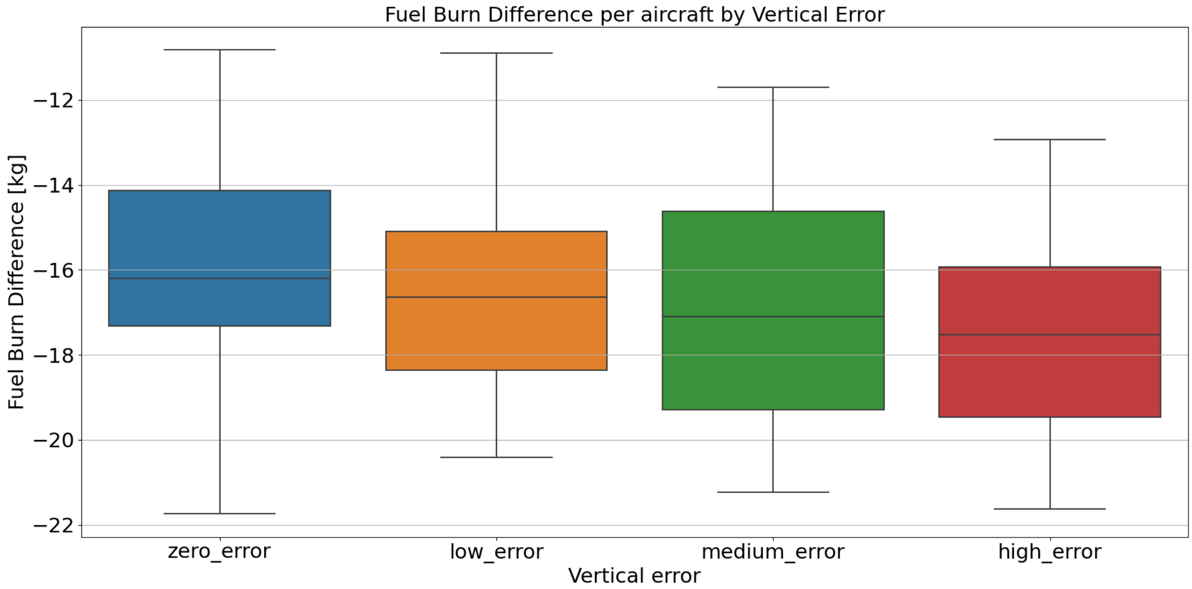

Figure 4: *Fuel Burn difference per aircraft grouped by vertical error*

correction is performed using Dunn's test.

The results show significant differences between several buffer comparisons. The minimal buffer is significantly different from both high (p = 0.00) and medium (p = 0.0033). At the same time, the low buffer is also significantly different from high (p = 0.00) and medium (p = 0.0097). Medium and high exhibit a statistically significant difference (p = 0.0471). These findings highlight that minimal and low separation buffers have a notable effect on track miles, especially when compared to high and medium buffers.

The minimal buffer scenarios demonstrate the greatest track-mile reduction, with the lowest median value and the broadest IQR. Although the simulations with minimal buffers optimize trajectories efficiently, the increased variability indicates that the reduction in distance traveled compared to the baseline is less consistent. The low buffer scenario shows a reasonable decrease with less variability, as evidenced by a smaller IQR and overall spread, except for the single outlier. This trend continues in the medium buffer scenario, where median track-mile reduction drops further. Finally, the high buffer scenario exhibits the slightest reduction in track miles, with the highest median value and the tightest IQR, suggesting minimal but consistent track miles reduction.

The figure shows a clear trend where the reduction in track miles decreases as the separation buffer increases. This trend is expected because larger separation buffers result in more frequent trajectory deviations to maintain safe separation between aircraft, which limits the potential for reducing track miles. As the buffer increases, the flexibility for optimizing trajectories decreases, leading to fewer opportunities for track mile reductions compared to scenarios with lower buffers.

5.3 Flight time

Figure 6 presents the flight time difference per aircraft compared to the baseline, grouped by separation buffer (left) and vertical error (right). Since both independent variables had a p-value less than 0.05, while airspace density had a p-value greater than 0.05, the effects of separation buffer and vertical error on flight time are discussed in more detail.

Effect of Separation Buffer and Vertical Error Statistical analysis using the Kruskal-Wallis test shows that separation buffer and vertical error have a significant effect on flight time, with both having a p-value of 0.00 and KW-statistics of 14.7267 and 30.7933, respectively. This indicates sufficient evidence to reject the null hypothesis for both variables, demonstrating that separation buffer size and vertical error changes lead to significant flight time variations. However, to determine which specific levels cause these differences, a post-hoc analysis with Bonferroni correction for both variables is performed using Dunn's test.

Regarding the buffer, minimal buffer showed significant differences compared to high (p = 0.0015) and low (p = 0.0315), while no significant differences were observed between medium and other levels. For the vertical error, zero error differed significantly from high (p = 0.00) and medium (p = 0.0021), while low error only showed a significant difference with

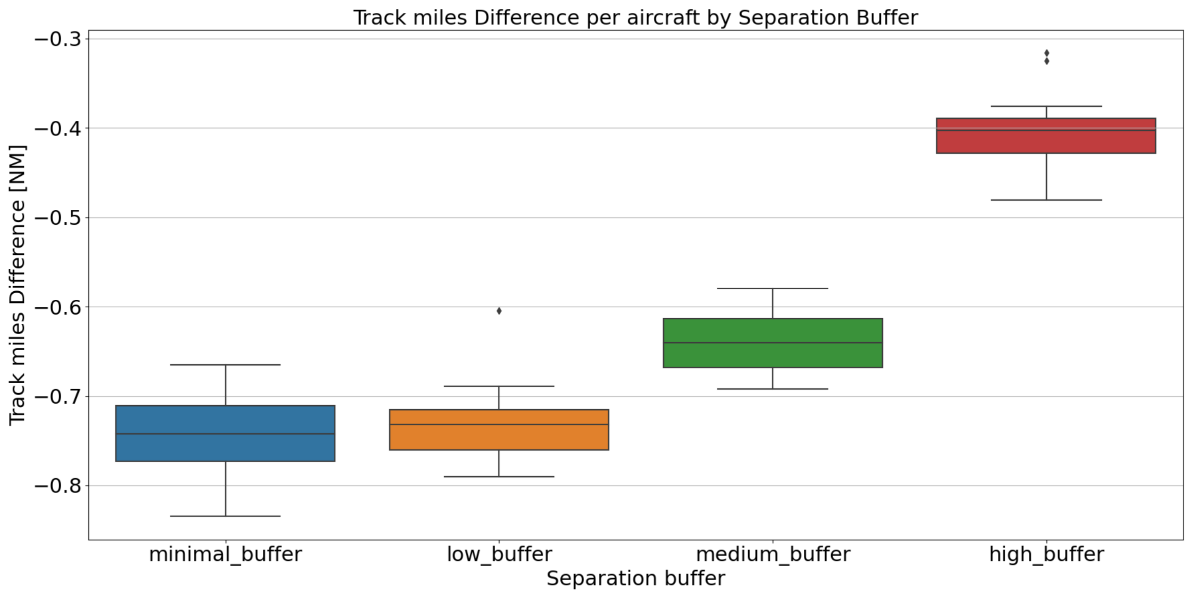

Figure 5: *Track miles difference with baseline per aircraft grouped by separation buffer*

high (p = 0.0029). These results suggest that both the buffer and vertical error levels influence flight time, with minimal buffer and zero error showing the most significant impacts.

As presented in the figure, a consistent pattern emerges between the two independent variables: as the separation buffer or vertical error increases, the reduction in flight time per aircraft decreases, meaning the total flight time tends to increase. In both cases, the smallest buffer and the lowest error exhibit the greatest median reduction in flight time, reflecting more efficient flight operations.

However, the two variables' overall spread of flight time reduction differs. The spread remains relatively consistent across the different buffer levels for the separation buffer, indicating that the variability in flight time reduction is similar regardless of buffer size. In contrast, the overall spread and the IQR increase for vertical error as the error level increases. This suggests that flight time reductions are more stable with lower error levels, but as the error grows, the results become more variable. This variability likely stems from greater deviations in trajectory adjustments when the system compensates for larger vertical errors, leading to less predictable flight time savings.

5.4 Optimizations done and constraining actions

The previously discussed metrics were all part of the operational efficiency category. However, examining how the independent variables affect the optimized trajectories category is important, specifically, how often an optimization or constraining action occurs.

The Kruskal-Wallis test determined that the only variable that has a significant effect on optimizations done per aircraft and constraining actions per aircraft was the separation buffer, KW-statistic = 58.7091, p = 0.00 and KW-statistic = 59.0810, p = 0.00, respectively. This suggests sufficient evidence to reject the null hypothesis, indicating that changes in separation buffer size lead to significant variations in the number of optimizations and constraining actions. Figure 7 illustrates these differences between buffer levels for the optimization done. The figure for the constraining actions can be found in Appendix C.2. As shown, the number of optimizations decreases as the separation buffer increases. This is expected behavior, as a larger buffer leads to more conservative decisions by the controller when optimizing trajectories.

Dunn's test was performed for both metrics to assess differences based on the separation buffer. For optimizations done, minimal buffer showed significant differences compared to high and medium (p = 0.00). Low buffer also differed significantly from high. Regarding constraining actions, minimal buffer again differed significantly from medium and high (p = 0.00), while high and low differed significantly. These findings indicate that minimal and high buffers had the most notable effects on optimizations and constraining actions, with minimal consistently showing significant differences across the metrics.

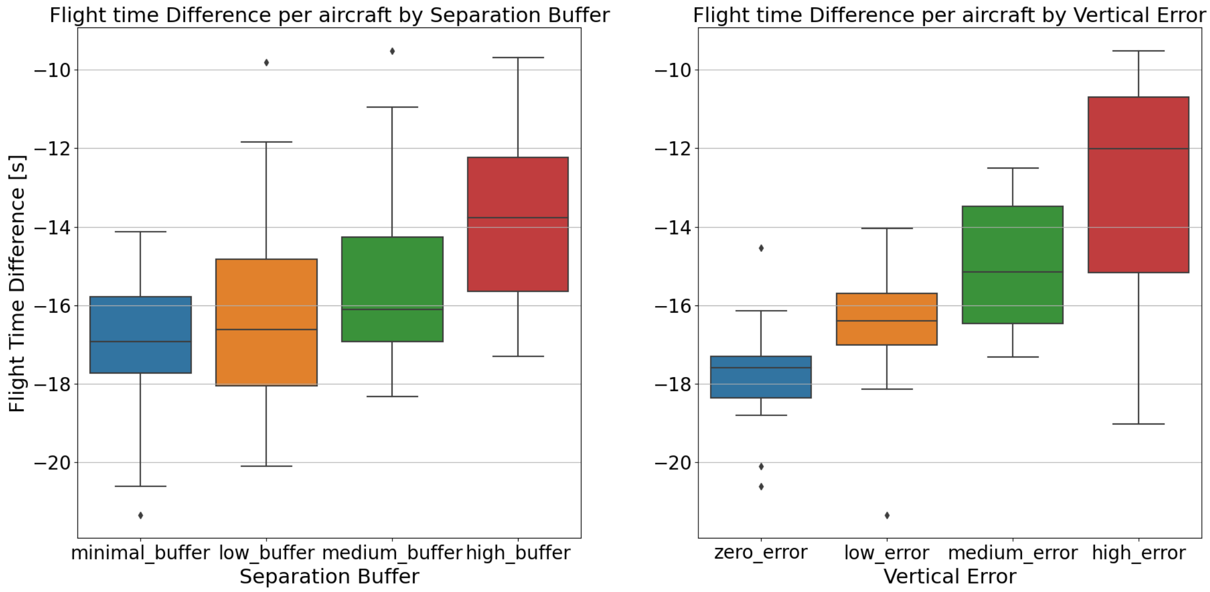

Figure 6: *Flight time difference per aircraft grouped by separation buffer and vertical error*

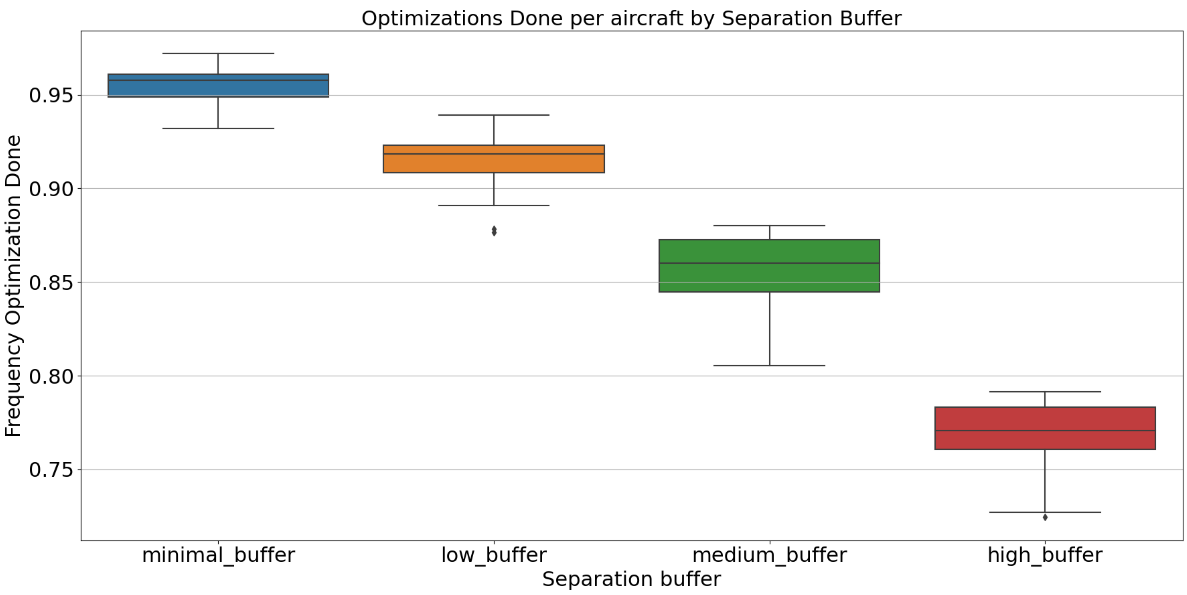

Figure 7: *Optimizations done per aircraft grouped buffer*

5.5 Correlation analysis

While previous analyses focused on comparing individual metrics, it is equally important to explore potential relationships between metrics from different and the same categories. Investigating combined metrics allows a deeper understanding of how various operational efficiency, safety margin, and trajectory optimization factors interact.

Fuel burn and work done The relationship between fuel consumption and work done was analyzed using linear regression (R^2 = 0.92) and Spearman's rank correlation (0.95). The strong Spearman coefficient confirmed a strong monotonic relationship, while the linear regression indicated a strong positive linear trend. These results were expected and validated the correct behavior. The respective figure is presented in Appendix C.3.

Fuel burn and Optimizations done Another interesting combination is the normalized fuel burn difference per aircraft relative to the baseline and its relationship to the number of optimizations per aircraft. Figure 8 shows a strong negative linear relationship (R^2 = 0.54), indicating that more optimizations consistently reduce fuel burn per aircraft. Additionally, Spearman's rank coefficient of -0.72 suggests that this relationship is strongly negative monotonic. This underscores the effectiveness of trajectory optimizations in enhancing fuel efficiency and operational performance.

Fuel burn and (horizontal) flight time As an aircraft approaches the runway, a smooth, fast, and continuous descent, characterized by low horizontal and total flight time, is ideal. However, horizontal flight should be as efficient as possible if necessary. Therefore, examining whether there is a correlation between fuel burn and horizontal or total flight time is important. The R^2 values suggest that the relationship is not linear, with 0.14 for horizontal flight time and 0.01 for total flight time. Furthermore, Spearman's coefficients of -0.38 and 0.13 indicate that the relationship is not strongly monotonic. The respective figures are shown in Appendix C.5.

Potential conflict and Loss of Separation The relationship between the frequency of potential conflicts and the frequency of loss of separation events, as shown by Figure 9, reveals a very weak negative linear relationship (R^2 = 0.07). Also, Spearman's rank coefficient of -0.29 suggests a weak negative monotonic relationship between the two metrics, indicating that as conflict duration increases, there is a slight tendency for the frequency of loss of separation events to decrease. However, it can be observed that the densities are clustered. Focusing on minimal, a strong negative linear relationship between potential conflicts and loss of separation events is revealed, as indicated by an R^2 value of 0.88. The figure for the minimal density is provided in Appendix C.4.

6 Discussion

This study evaluated the impact of varying airspace density, separation buffers, and vertical error in ADS-C data on operational efficiency and safety margins using 64 simulation configurations compared to the baseline in lower airspace. The discussion focuses on the significant findings related to fuel burn, track miles, flight time, and the impact of trajectory optimizations.

6.1 Results

Fuel burn An important finding is the consistent reduction in fuel consumption across all airspace densities, compared to the baseline, due to the implementation of the optimization tool. This outcome is expected, as the baseline scenarios do not permit trajectory optimizations, while the tool enhances efficiency by adjusting flight paths where possible.

The analysis of the fuel burn was affected differently depending on the independent variables. While airspace density did not have a statistically significant effect, it is worth noting that the relatively low p-value (0.09) suggests a potential influence that could become more apparent with a larger sample size or more sensitive measures. This also applies to the work done metric. As depicted in the airspace density results, the minimal, low, and high-density scenarios all have relatively close median values for fuel burn per aircraft. The high-density scenario exhibited the largest median reduction in fuel burn, but this improvement in efficiency came with an increased number of conflicts overall. This indicates that higher densities may create more opportunities for fuel savings through trajectory optimizations, but they also lead to higher operational risk due to more conflict situations.

It is essential to highlight that the optimization tool utilized in these simulations aims to prevent potential conflicts by using ADS-C data but does not actively resolve conflicts once they occur. In real-life operations, this could mean that under high-density conditions, the tool's ability to optimize trajectories becomes constrained by frequent conflicts, resulting in fewer optimization opportunities and reduced overall fuel savings. Despite the similar fuel savings achieved in both the minimal and high-density scenarios, the minimal-density configuration stands out as a more desirable option. The minimal-density

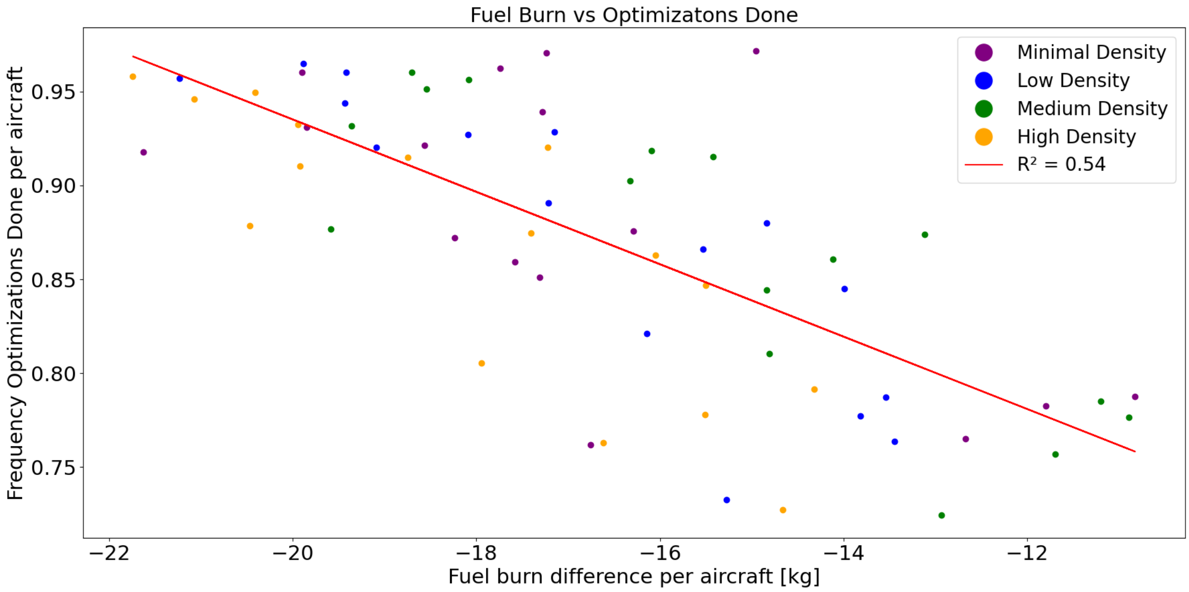

Figure 8: *Comparison of fuel burn difference per aircraft vs. optimizations done per aircraft*

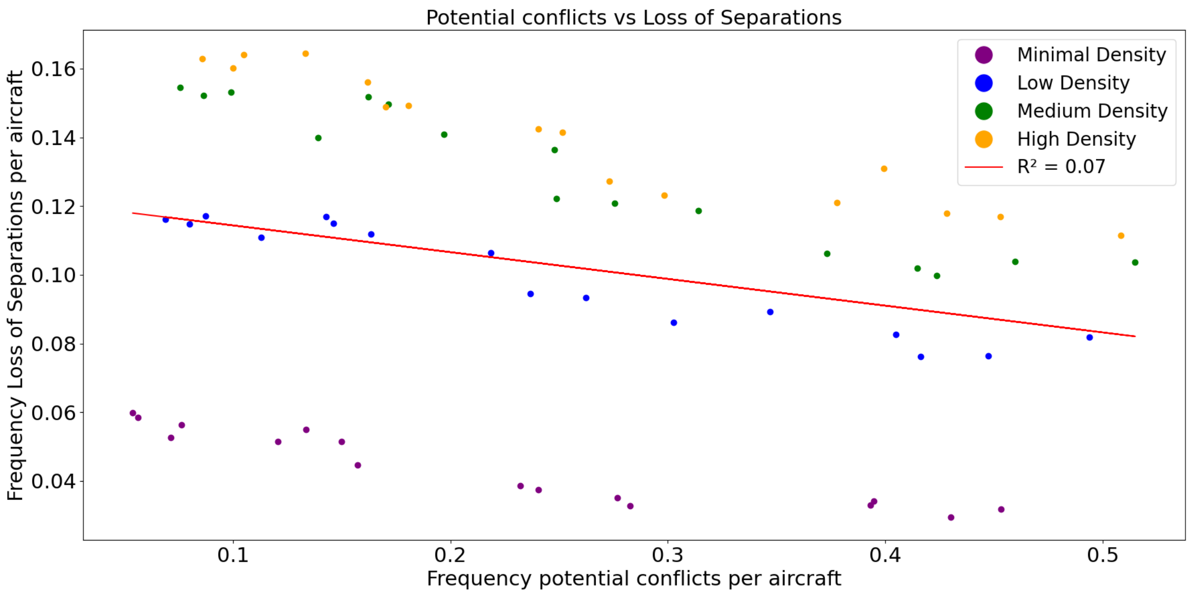

Figure 9: *Comparison of Potential Conflict per aircraft vs. Loss of Separation per aircraft*

scenario results in fewer conflicts and offers more consistent optimization opportunities, thus striking a better balance between operational efficiency and safety.

In contrast, separation buffer significantly impacted fuel burn, with smaller buffers resulting in more significant fuel savings. This finding aligns with expectations, as smaller buffers allow for more aggressive trajectory optimizations, reducing fuel burn. The post-hoc analysis using Dunn's test indicated that minimal and low separation buffers significantly impact fuel burn more than higher separation buffers. These results demonstrate a clear trade-off between operational efficiency and safety margins - larger separation buffers lead to more conservative operations and reduced fuel savings but likely enhance safety by providing more room for error. Moreover, as just described, the minimal buffer scenarios showed the greatest reduction in fuel burn per aircraft, with a median value of -19.4 kg per aircraft. If this value is extrapolated to the annual average of 464,000 flights in 2023, it amounts to approximately 9.05 million kilograms of fuel saved annually.

While these numbers should be viewed within the context of the simulations, they underscore the practical value of trajectory optimization with ADS-C in improving fuel efficiency, an important factor given the aviation industry's emphasis on reducing carbon emissions and operational costs. Trajectory optimization is a crucial component of Trajectory-Based Operations (TBO), which aims to enhance air traffic management by allowing more dynamic and flexible routing based on real-time data. However, it is essential to note that the trajectories were not conflict-free. Despite this, trajectory optimization shows significant potential for improving operational efficiency.

Interestingly, vertical error in ADS-C data did not significantly affect fuel burn. However, increasing fuel savings with increasing vertical error was observed. This counterintuitive finding may be explained by cases where higher vertical error introduces opportunities for more frequent optimizations, as aircraft deviate more from their actual flight path in the data, inadvertently creating room for efficiency improvements.

Interestingly, vertical error in ADS-C data did not significantly affect fuel burn. However, increasing fuel savings with increasing vertical error was observed. This counterintuitive finding may be explained by cases where higher vertical error introduces opportunities for more frequent optimizations, as aircraft deviate more from their actual flight path in the data, inadvertently creating room for efficiency improvements. However, the need for accurate ADS-C data remains paramount, as safety is the most important factor, even if this results in less efficient flights.

Track miles Separation buffer was also found to significantly affect track miles, with smaller buffers resulting in a greater reduction in distance flown. Similar to fuel burn, resulting from Dunn's test, smaller separation buffers also significantly affect track miles compared to larger buffers. This finding reinforces the relationship between buffer size and operational flexibility: smaller buffers allow for more efficient routing, while larger buffers necessitate deviations to maintain safe separation. As with fuel burn, this highlights a key operational trade-off - controllers must balance the desire for efficiency against the need for safety when setting separation standards.

Interestingly, neither airspace density nor vertical error had a statistically significant impact on track miles. This suggests that the primary determinant of track miles in these simulations is the controller's ability to safely optimize trajectories, which is heavily influenced by separation buffer size rather than other factors like airspace density or vertical error.

Flight time Both separation buffer and vertical error had significant effects on flight time. As with fuel burn and track miles, smaller buffers resulted in shorter flight times, while larger buffers led to longer flights. The impact of vertical error on flight time followed a similar pattern, with greater error leading to more variability in flight time reductions. This was also evident in Dunn's test, where smaller buffer sizes and lower error levels significantly reduced flight time. This suggests that the system's ability to optimize flight trajectories is more sensitive to vertical error, likely because larger errors necessitate more frequent adjustments to maintain safe separation.

The consistent relationship between separation buffer, vertical error, and flight time further underscores the trade-off between efficiency and safety. While smaller buffers and lower error levels allow for more efficient operations, they may also increase the risk of conflicts or loss of separation events.

Optimizations and Constraining Actions The number of optimizations performed per aircraft was only significantly affected by separation buffer size, with smaller buffers resulting in more frequent optimizations. This finding is consistent with the fuel burn, track miles, and flight time results — smaller buffers allow for more aggressive trajectory adjustments, which improve efficiency but may come at the cost of safety. A similar trend was observed for constraining actions, but then negatively, so the amount of constraining actions increased with an increase in the buffer. This suggests that smaller buffers enable more efficient operations and require frequent intervention to maintain safe separation, highlighting the balance between efficiency and safety.

Correlation analysis The correlation analysis between fuel burn and work done confirmed a strong monotonic and linear relationship, validating the system's correct behavior. This indicates that as aircraft perform more work, such as maneuvering to maintain separation or adjust their flight paths, fuel burn increases proportionally. This is because maneuvers typically require additional energy, whether through changes in speed, altitude, or course corrections, all of which lead to higher fuel burn. These findings highlight the importance of optimizing air traffic management to reduce unnecessary maneuvers, which can lead to substantial fuel savings and decreased environmental emissions. The close relationship between these two metrics reflects the direct impact of increased operational effort on fuel efficiency.

Moreover, the strong negative correlation between fuel burn and the number of optimizations done reinforces the effectiveness of the optimization tool — more frequent optimizations consistently lead to improved fuel efficiency.

The results of the correlation analysis on fuel burn and horizontal flight time indicated little to no relationship between these metrics. This suggests that while flight time is an important operational metric, fuel efficiency may be more strongly affected by other factors, such as track miles.

Finally, when analyzing all simulations combined, the weak overall correlation between potential conflicts and loss of separation events suggests that these two metrics are unrelated. However, a strong negative correlation becomes evident when zooming in and analyzing each airspace density individually. This indicates that within each specific density level, there is a robust relationship between potential conflicts and loss of separation events. In particular, the strong negative relationship observed within the individual density scenario suggests that the system is highly effective at managing conflicts before they lead to a loss of separation. This finding demonstrates that while the overall correlation may appear weak across all densities combined, the system's ability to prevent safety violations is notably effective within individual density levels.

6.2 Limitations

This study has several limitations. The results are based on simulations, which may not fully capture the complexities of real-world operations, such as unpredictable weather conditions or pilot behaviors. While helpful for isolating variables, the controlled simulation environment may overlook dynamic factors in actual air traffic scenarios. Additionally, the vertical error introduced in ADS-C data was synthetic and simplified, potentially not accurately representing the types and distributions of errors encountered in actual operations. This could affect the normalization of the findings related to data inaccuracies.

Additionally, this study heavily relies on the performance models and aircraft characteristics of the BlueSky simulator. While these models provide a useful approximation of real-world performance, they may not capture the full range of aircraft behaviors or specific nuances in performance for different aircraft types and configurations. This limitation could affect the accuracy of absolute numbers related to fuel consumption, flight dynamics, and other operational metrics, especially when simulating highly diverse or less common aircraft. Moreover, any future updates or improvements to the BlueSky models could potentially alter the results of similar simulations, highlighting the dependence of this study on the current state of the simulator.

Furthermore, the study focused on specific efficiency and safety metrics like fuel burn, track miles, and conflicts. Other important factors, such as controller workload, passenger comfort, and broader environmental impacts, were not considered. This limited scope means that the overall effect and realism of the optimization tool on air traffic management may not be fully captured.

6.3 Recommendations for future research

To address these limitations, an interesting direction for future work would be to modify the tool so that it can be used by an air traffic controller in a real-time simulation exercise. This would allow for evaluating the tool's practical usability and efficiency in dynamic, real-time settings. Additionally, integrating ADS-C data into such simulations could be tested as an aid to current conflict detection mechanisms used by air traffic controllers. This would help assess whether ADS-C can enhance conflict detection and resolution capabilities, providing controllers with more accurate and timely information and potentially improving trajectory optimizations.

Additionally, incorporating more complex and realistic error models in ADS-C data would better assess the system's robustness to data inaccuracies. Expanding the set of performance metrics to include environmental impacts, such as CO_2 emissions, economic factors, and human factors like controller and pilot workload, would offer a more comprehensive evaluation of the tool's impact. Developing adaptive optimization algorithms that can adjust to varying traffic densities and separation requirements in real-time could further enhance the scalability and effectiveness of the tool in different operational contexts.

7 Conclusion

This research evaluated how the availability of detailed trajectory information and increased predictability through ADS-C data impacts air traffic control procedures, specifically focusing on operational efficiency and safety margins. Through 64 simulation configurations, varying factors like airspace density, separation buffer size, and vertical error in ADS-C data, this study has provided valuable insights into the relation between these factors and the potential for optimizing air traffic procedures in lower airspace.

A key finding is the significant role of separation buffer size, which emerged as the most influential factor affecting all analyzed metrics. Smaller separation buffers led to greater operational efficiency, allowing for more aggressive trajectory optimizations and reducing fuel consumption, distance flown, and overall flight time. However, this came at the cost of increased safety risks, as smaller buffers also required more frequent interventions to maintain safe separation between aircraft.

In contrast, airspace density did not significantly affect fuel burn, track miles, or flight time. However, the relatively low p-values suggest a potential influence that could be further explored in future studies. Interestingly, the high-density scenarios exhibited the greatest fuel savings but also resulted in the highest frequency of conflicts, indicating a trade-off between efficiency and safety. This finding underscores the challenge of managing high-density airspace environments, where increased opportunities for fuel savings can come at the cost of operational safety.

The introduction of vertical errors in ADS-C data did not significantly impact fuel burn or track miles. Still, a trend showed increased fuel savings as vertical error increased. This counterintuitive result suggests that the added variability introduced by vertical error may create more opportunities for the optimization tool to adjust flight paths, leading to efficiency improvements. Nonetheless, accurate ADS-C data remains paramount, as safety is the most important factor, even if this leads to less efficient flights.

The findings from this study strongly support the potential of Trajectory-Based Operations (TBO) to enhance air traffic control procedures. By utilizing real-time ADS-C data to predict aircraft trajectories more accurately, TBO enables more dynamic and flexible routing, improving operational efficiency while maintaining safety standards. The increased predictability afforded by ADS-C technology allows air traffic controllers to make better-informed decisions about optimizing flight paths, especially when managing intersecting trajectories in busy airspace. However, the results also highlight the importance of carefully balancing operational efficiency and safety, particularly in high-density airspace and when utilizing smaller separation buffers.

In conclusion, using ADS-C data for trajectory optimization shows significant promise for improving operational efficiency, particularly in reducing fuel burn and flight times. The results suggest that, with enhanced predictability and more accurate trajectory information, air traffic control procedures can be refined to allow for more efficient operations. This aligns with the broader goals of TBO, which seeks to use advanced surveillance technologies to create a more efficient, flexible, and sustainable air traffic management system.

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A Experimental test matrix

Table 3: *Complete experimental test matrix*

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
1	Minimal	Minimal	Zero error
2	Minimal	Minimal	Low Error
3	Minimal	Minimal	Medium Error
4	Minimal	Minimal	High Error
5	Minimal	Low	Zero error
6	Minimal	Low	Low Error
7	Minimal	Low	Medium Error
8	Minimal	Low	High Error
9	Minimal	Medium	Zero error
10	Minimal	Medium	Low Error
11	Minimal	Medium	Medium Error
12	Minimal	Medium	High Error
13	Minimal	High	Zero error
14	Minimal	High	Low Error
15	Minimal	High	Medium Error
16	Minimal	High	High Error
17	Low	Minimal	Zero error
18	Low	Minimal	Low Error
19	Low	Minimal	Medium Error
20	Low	Minimal	High Error
21	Low	Low	Zero error
22	Low	Low	Low Error
23	Low	Low	Medium Error
24	Low	Low	High Error
25	Low	Medium	Zero error
26	Low	Medium	Low Error
27	Low	Medium	Medium Error
28	Low	Medium	High Error
29	Low	High	Zero error
30	Low	High	Low Error
31	Low	High	Medium Error
32	Low	High	High Error
33	Medium	Minimal	Zero error
34	Medium	Minimal	Low Error
35	Medium	Minimal	Medium Error
36	Medium	Minimal	High Error
37	Medium	Low	Zero error
38	Medium	Low	Low Error
39	Medium	Low	Medium Error
40	Medium	Low	High Error
41	Medium	Medium	Zero error
42	Medium	Medium	Low Error
43	Medium	Medium	Medium Error
44	Medium	Medium	High Error
45	Medium	High	Zero error
46	Medium	High	Low Error
47	Medium	High	Medium Error

Continued on next page

Table 3 – continued from previous page

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
48	Medium	High	High Error
49	High	Minimal	Zero error
50	High	Minimal	Low Error
51	High	Minimal	Medium Error
52	High	Minimal	High Error
53	High	Low	Zero error
54	High	Low	Low Error
55	High	Low	Medium Error
56	High	Low	High Error
57	High	Medium	Zero error
58	High	Medium	Low Error
59	High	Medium	Medium Error
60	High	Medium	High Error
61	High	High	Zero error
62	High	High	Low Error
63	High	High	Medium Error
64	High	High	High Error

B Difference between IPI and EPP

Table 4: *IPI and EPP comparison [17]*

Item		Intermediate Projected Intent	Extended Predicted Profile
General	Maximum number of trajectory change points	10	128
	Maximum look ahead time	0-255 mins	15-1200 mins
TCP Estimated State	TCP location	Yes (sequence of bearing and distance from start point)	Yes (Latitude and longitude)
	TCP altitude	Yes	Yes
	TCP time	Yes	Yes
	TCP speed	No	Yes
TCP Specification	TCP waypoint name (if appl.)	No	Yes
	TCP type specification	No	Yes
	Level change, e.g. Top of Climb (TOC) / Top of Descent (TOD)	Yes	Yes
	Lateral change	Yes	Yes
	Speed change start	Implementation dependant (at least one of two provided)	Yes
	Speed change end		Yes
	Waypoint	Depends if coincides with lateral/vertical/speed change	Yes
Turn Geometry	Fly-by turn radius	No	Yes
	Fly-over turn radius/radii	No	No
	Supports Radius to Fix (RF)legs	No	Yes
Additional Data	Gross mass	No	Yes

C Additional figures

This section presents additional figures complementary to the results.

C.1 Loss of Separation frequency per aircraft

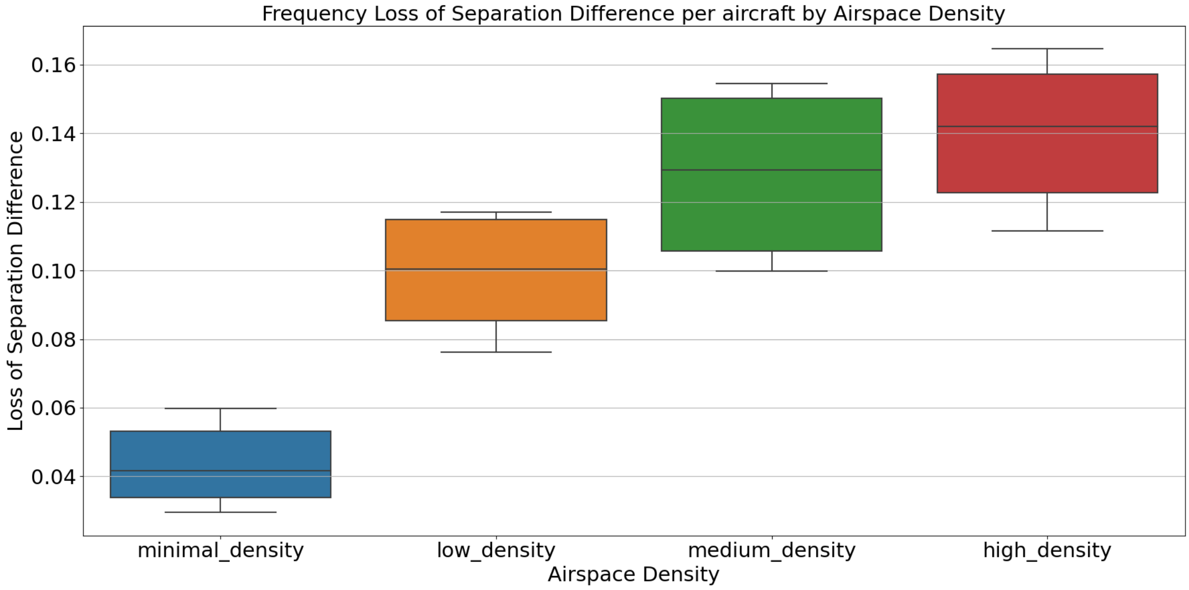

Figure 10: *Loss of Separation difference with baseline per aircraft grouped by density*

C.2 Frequency constraining actions per aircraft

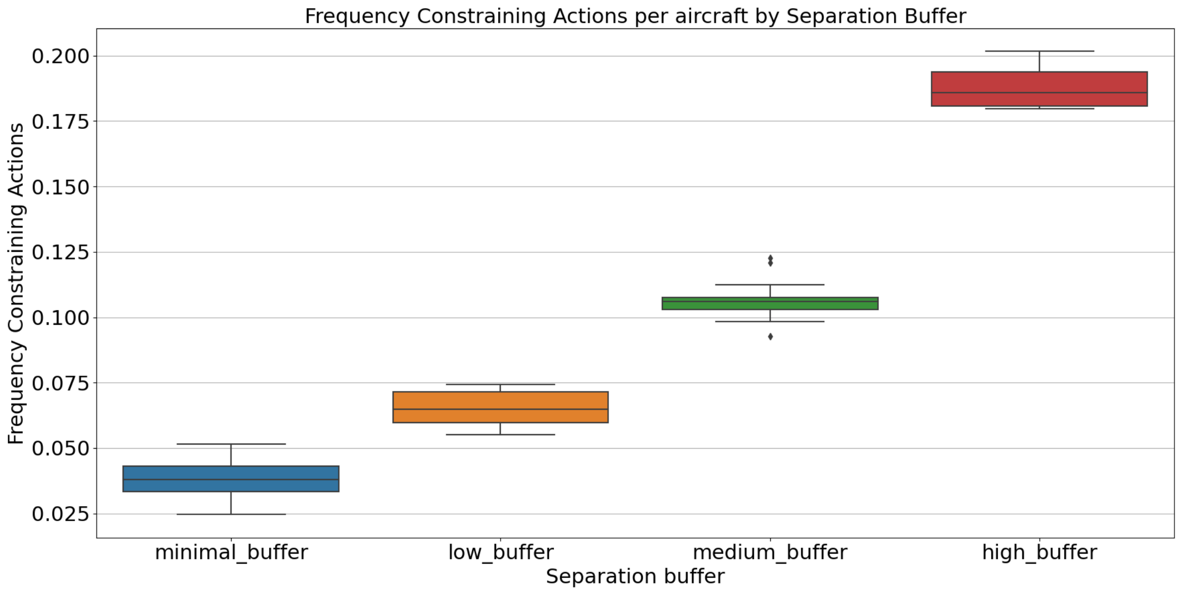

Figure 11: *Constraining actions per aircraft grouped buffer*

C.3 Correlation between fuel burn and work done

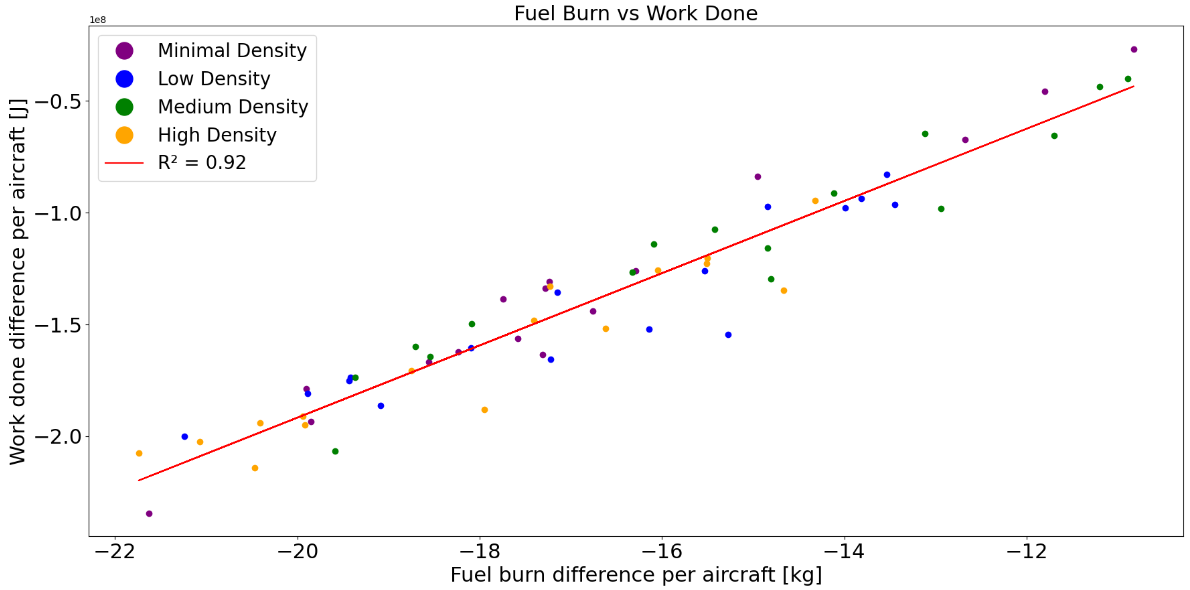

Figure 12: *Comparison of fuel burn difference per aircraft vs work done difference per aircraft*

C.4 Correlation between potential conflict and LoS focused on minimal density

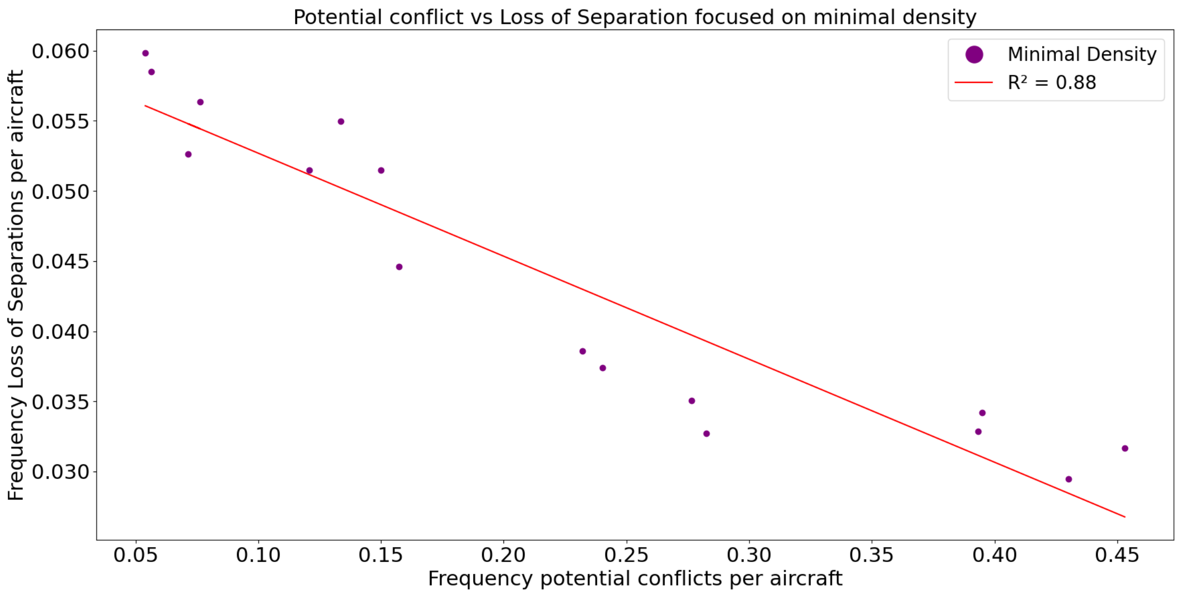

Figure 13: *Comparison of Potential Conflict per aircraft vs. Loss of Separation per aircraft focused on minimal density*

C.5 Correlation between fuel burn and (horizontal) flight time

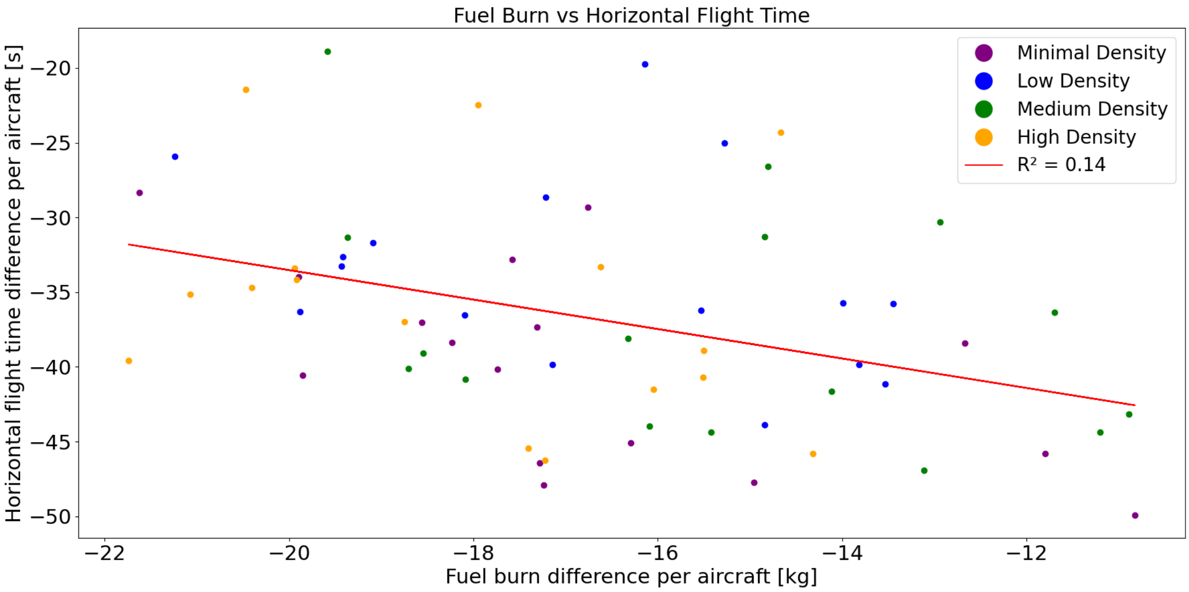

Figure 14: *Comparison of fuel burn per aircraft vs. horizontal flight time per aircraft*

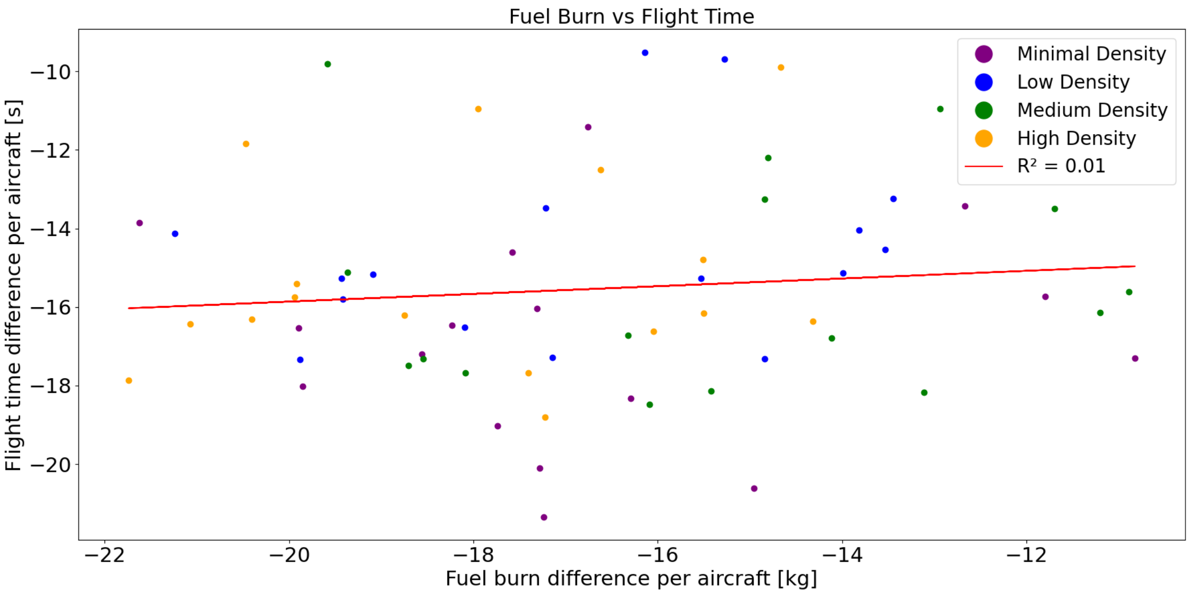

Figure 15: *Comparison of fuel burn per aircraft vs. flight time per aircraft*

Part II
Preliminary Report

1 Introduction

At the end of July 2023, a serious concern occurred at Amsterdam Airport Schiphol. A KLM Boeing 737 and an Airbus A320, leased by TUI Netherlands, were on their respective approaches to the airport. The Airbus appeared to have gone off track and headed towards the incorrect runway. Simultaneously, The Boeing was descending Schiphol using the appropriate runway. The two aircraft were getting dangerously close to each other, with only a small gap between them. Fortunately, the air traffic controller (ATCO) intervened correctly. They instructed the Boeing to steer left and the Airbus to turn right to prevent a potential collision. The exact cause of the incident is still unknown and cannot be confirmed yet by LVNL, as the research is still ongoing (Sajet, 2023). However, this incident might have been detected earlier or avoided if the two aircraft had used Automatic Dependent Surveillance - Contract (ADS-C) datalink.

ADS-C is a surveillance technology for tracking and monitoring aircraft during a flight. Instead of using radar on the ground, ADS-C relies on the aircraft's onboard systems, such as the Flight Management System (FMS), to automatically send information about its position, altitude, velocity, navigational intent, and other essential information to ground-based Air Traffic Control (ATC) systems using air-to-ground datalinks. Consequently, the gathered information can be displayed on the controller's screen and used as input for ground-based tools. So, no pilot manual intervention is needed. The circumstances in which ADS contracts are initiated, and the data they include are determined by the type of the service (ICAO, 2017).

The latest generation of Air-to-Ground Datalink (AGDL), known as Air Traffic Services B2 (ATS B2) and recently developed by RTCA/EUROCAE (EUROCAE, 2023), is currently being introduced into European airspace. As mandated by the European Union (EU), effective from 31 December 2027, aircraft receiving their first airworthiness certification on or after this date must be capable of downlinking and processing ADS-C Extended Projected Profile (EPP) data, which is part of ATS B2 (European Commission, 2021). An important element of this AGDL implementation is the availability of detailed trajectory information with flight intent. This application improves predictability, allowing for more accurate predictions of an aircraft's intentions and destination (EUROCONTROL, 2023).

Within this context, ADS-C is an important enabler for the concept Trajectory Based Operations (TBO), which represents the future of air traffic management. Unlike traditional airspace-based operations that focus on managing aircraft within predefined airspace sectors, TBO emphasizes managing individual aircraft trajectories. This approach aims to create an environment where the actual flight trajectory closely aligns with the user-preferred trajectory, reducing conflicts and improving efficiency. TBO uses detailed 4D trajectory data, which includes latitude, longitude, altitude, and time, to optimize flight paths and enhance decision-making processes for all stakeholders (Tielrooij et al., 2022).

By continuously transmitting detailed data about an aircraft's current and intended flight path, ADS-C enhances the predictability and synchronization of trajectories. This data integration supports the key objectives of TBO, such as optimizing flight paths, reducing fuel consumption, and minimizing environmental impact. Additionally, by providing detailed intent data, ADS-C enhances the capability of ATC systems to detect and resolve potential conflicts early, ensuring safe separation while optimizing trajectories. The implementation of ATS B2 ADS-C is thus a significant step towards realizing the full potential of TBO in modernizing air traffic management and achieving safer, more efficient, and environmentally sustainable operations.

1.1. Problem statement

Since 30 May 2022, ATS B2 ADS-C has been operational at the Maastricht Upper Area Control Centre (MUAC). This early implementation demonstrates European Organisation for the Safety of Air Navigation (EUROCONTROL) as one of the world's leading Network Manager (NM) in adopting datalink technology for Air Traffic Management (ATM) (EUROCONTROL, 2023). As MUAC focuses primarily on the upper area of the airspace, more research is needed on the sub-domain of ATM that has not been explored to a great extent: application of this detailed trajectory information in lower airspace as opposed to Upper Airspace Control (UAC). The term 'lower airspace' in this context refers to the region managed by Approach Control (APP) and Area Control Center (ACC), generally extending from FL0 (Flight Level) up to approximately FL245 (EUROCONTROL, 2004).

The research will be situated within the current re-design of the Dutch airspace as planned in the Dutch Airspace Redesign Program (DARP). It will also align with the existing operational concept of Luchtverkeersleiding Nederland (LVNL) for Trajectory Based Operations (TBO) implementation as published by the Knowledge and Development Centre (KDC) (Tielrooij et al., 2022). Also, this research is in support of the process from a tactical to a planned environment, as pursued with TBO. Investigating using datalink in lower airspace could lead to significant advancements in air traffic management, enhancing safety, efficiency, and predictability.

1.2. Research significance

The significance of this study lies in its potential to advance the field of ATM by utilizing ADS-C technology to improve ATC procedures within lower airspace. Existing research on ADS-C, specifically the EPP, has predominantly focused on its applications, accuracy, and usage, but not necessarily on this domain (Bronsvoort et al., 2016; Sosovicka et al., 2015). Additionally, a demonstration report by SESAR3 Joint Undertaking focused mainly on the applications of ADS-C in the upper airspace. One outcome of this report is that Conflict Detection and Resolution (CD&R) can be improved using ADS-C EPP data. Research by Hao et al. (2018) also focused on conflict detection within TBO contexts. Furthermore, the European Union's mandate for the adoption of ATS B2 ADS-C by 2027 underscores its significance in modernizing ATM systems (European Commission, 2021).

This research builds on these studies and reports by extending the investigation to an area that has not been extensively explored. Current implementations, such as those at the MUAC, focus primarily on upper airspace, leaving a gap in understanding how these technologies can be adapted for and benefit at lower altitudes. This study aims to bridge this gap by examining the specific challenges and opportunities presented by ADS-C in the lower airspace managed by APP and ACC.

The study is expected to provide new insights into the practical applications of ADS-C in these areas, particularly in improving operational safety and efficiency. By systematically analyzing the effects of detailed trajectory information and flight intent on ATC procedures, this research will offer potential benefits on how these technologies can enhance predictability, reduce conflicts, and optimize flight paths in lower airspace.

1.3. Report structure

The remainder of this paper is structured as follows: Chapter 2 provides the background on TBO and datalink technology, including ADS-C. Chapter 3 presents an explanation of airspace procedures, including separation minima and conflict detection and resolution procedures. Chapter 4 details the research questions and hypotheses. Chapter 5 details the thesis framework used in this study. Finally, Chapter 6 describes the research methodology and experimental setup.

2

Background

This chapter will delve deeper into the background of the problem. It will begin with an explanation of Trajectory Based Operations (TBO), followed by a discussion of datalinks. Furthermore, the Automatic Dependent Surveillance - Contract (ADS-C) datalink will be elaborated upon, including its applications and challenges.

2.1. Trajectory Based Operations

TBO is a crucial concept in modern Air Traffic Management (ATM), designed to reach the performance targets set by the Single European Sky ATM Masterplan. The International Civil Aviation Organisation (ICAO) introduced the Global ATM Operation Concept (GATMOC) (ICAO, 2005), which aims to shift the focus from airspace-based ATM to a trajectory-based approach (Bronsvoort et al., 2016). The essence of TBO is to create an ATM environment where the actual flight trajectory closely aligns with the user-preferred trajectory. This method seeks to reduce potential conflicts and manage demand/capacity imbalances more effectively and efficiently. Central to TBO is the utilization of a 4-Dimensional (4D) flight trajectory, such as the Extended Projected Profile (EPP), which encompasses the three spatial dimensions[1] plus time. This trajectory can be collaboratively developed, managed, and shared, providing a common reference for decision-making among all stakeholders (Tielrooij et al., 2022). A schematic picture of a 4D trajectory is given in Figure 2.1.

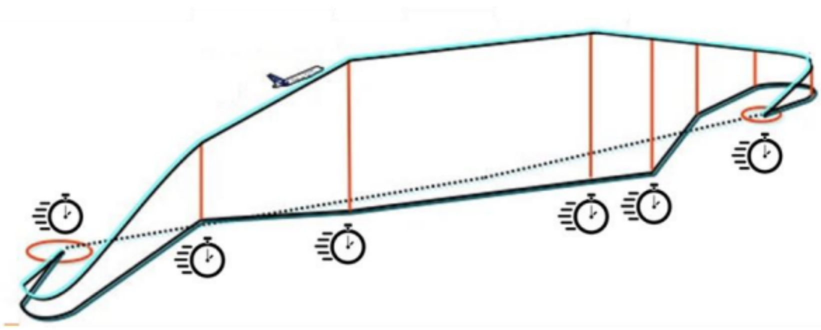

Figure 2.1: 4D trajectory (Tielrooij et al., 2022)

The concept of managing air traffic through predetermined trajectories can be traced back to early ATM systems that relied heavily on ground-based navigation aids. Over the decades, the advancement in satellite navigation and data communication technologies paved the way for more sophisticated approaches like TBO. Key milestones include the introduction of GPS-based navigation, the development of Automatic Dependent Surveillance-Broadcast (ADS-B), and Collaborative Decision-Making (CDM) frameworks (ICAO, 2016a).

According to Bronsvoort et al. (2016), TBO centers around two elements:

1. **Performance Based Navigation (PBN)**: This is a modern concept for defining and implementing navigation in aviation that allows for the precise and efficient use of airspace and air traffic routes. It differs

[1] Latitude, longitude, and altitude

from traditional navigation, which relies heavily on ground-based navigation aids, by using satellite systems and onboard navigation technology. PBN enables aircraft to fly a specific path with greater accuracy, flexibility, and efficiency.

2. **Trajectory Management (TM)**: TM is the systematic process of planning, monitoring, and adjusting the flight paths of aircraft to optimize airspace capacity and ensure safe, efficient operations. It involves coordinating the trajectories of individual aircraft to prevent conflicts and minimize delays, taking into account real-time factors such as weather conditions, air traffic density, and airspace restrictions. By managing trajectories proactively, ATC can facilitate smoother flight paths, reduce fuel consumption, and enhance overall operational efficiency. Additionally, TM enables a shared understanding between pilots and controllers of an aircraft's intended path, allowing for better synchronization between airborne and ground-based systems. This differs from conventional ATC as it focuses on proactive, real-time adjustments to optimize aircraft trajectories. In contrast, traditional ATC often relies on reactive measures to resolve conflicts and manage separations as they arise.

In the context of the Dutch airspace, particularly for the Schiphol operation, TBO is expected to focus mainly on the departure and arrival phases of flight, where significant benefits are expected. These benefits include improved predictability of trajectories, as well as safety, efficiency, and capacity. Additionally, the environmental impact is also expected to be reduced due to the more direct routing and optimum trajectories (Tielrooij et al., 2022).

Previous research has already been conducted on the potential of TBO to reduce the environmental impact through optimized trajectories. Liu et al. (2021) highlights the efficiency gains possible by tailoring 4D trajectories (incorporating three spatial dimensions and time) to the specific operational conditions and constraints faced by flights, ranging from airspace congestion to air traffic control mandates. Ahmed et al. (2021) also focuses on optimizing 4D trajectories to create more efficient flight paths that minimize fuel consumption and emissions. The study contrasts these optimized trajectories with standard flight paths to demonstrate the potential reductions in fuel and emissions. The results provide quantifiable environmental benefits, showcasing substantial improvements over conventional methods.

Despite the clear advantages, the transition to TBO is not without challenges. Regulatory frameworks need to be harmonized across different jurisdictions to ensure seamless operations. Interoperability between different systems is crucial, requiring significant investment in technology and infrastructure. Training for air traffic controllers and pilots is another critical aspect, as they must adapt to new procedures and tools (ICAO, 2016a).

2.2. Datalink

In aviation, datalink technology is a key element in modernizing air-ground communication, marking a significant shift away from traditional voice-based methods. The evolution of this technology can be traced back to the early days of aviation communication, where voice communication over radio was the primary method. However, the limitations of voice communication, such as frequency congestion and communication errors, highlighted the need for more reliable and efficient methods. Consequently, digital communication methods were developed, facilitating direct communication between aircraft and ground stations, including those operated by Air Navigation Service Providers (ANSPs) and airlines. The term 'datalink' broadly encompasses three main components: applications, infrastructure, and standards (de Gelder et al., 2022).

2.2.1. Components of datalink

Datalink applications provide operational services and benefits to users in the cockpit and on the ANSP side. They include ADS-C and Controller-Pilot Datalink Communications (CPDLC). ADS-C consists of automated, periodic, or event-triggered reports that provide essential data for the controllers and their supporting tools and processes. Additionally, CPDLC includes both predefined and free-text messages designed for communications, serving as a supplement to, or replacement for, existing Very High Frequency (VHF) communications (de Gelder et al., 2022).

The infrastructure supporting datalink contains many components, including onboard avionics, ANSP interfaces, and all underlying networks and sub-networks. Among these networks are Aircraft Communications and Reporting System (ACARS) and Aeronautical Telecommunications Network (ATN). ACARS is a globally implemented system that enables digital datalink messaging between air and ground, functioning on a protocol developed by Aeronautical Radio Incorporated (ARINC). In contrast, the ATN initiative originated in Europe, designed to overcome the limitations of the ACARS network. It offers enhanced transmission speeds, thereby reducing message latency, and boasts greater robustness compared to ACARS. Sub-networks include VHF Datalink (VDL) Mode 2 and Satellite Communications (SATCOM), where the former serves as the method for VHF communication, facilitating the exchange of messages or data sets between airborne and ground-based systems. SATCOM relies on satellites to send messages and data sets between air and ground systems. It can act as a supplement to VDL Mode 2 in regions where it is either unavailable or impractical (de Gelder et al., 2022).

Given the global nature of aviation, datalink technology adheres to international standards for developing infrastructure and utilizing applications. These standards ensure interoperability and consistency across various geographic regions and aircraft types. Three main standards have been developed, each building on the previous one: Future Air Navigation Systems (FANS) 1/A[2], ATS B1, and ATS B2. FANS 1/A, developed in the early 1990s, enabled CPDLC and ADS-C applications with a limited set of messages and data fields, respectively. Subsequently, the ATS B1 standard was developed. However, it supports only CPDLC applications with an updated message set and does not include ADS-C capabilities. The latest standard, ATS B2, is already in operation but is still being refined. ATS B2 does support CPDLC and ADS-C data link applications to the fullest extent, with the highest number of available messages and datasets. It has two revisions, Rev A and Rev B. Rev A is in operation, and Rev B is still being defined (de Gelder et al., 2022).

2.2.2. Benefits and challenges

Adopting datalink technology offers numerous benefits, including improved communication accuracy, reduced workload for pilots and controllers, and enhanced overall efficiency of air traffic management. By replacing voice communications with digital messages, datalink minimizes the risk of miscommunication and allows for more straightforward and precise exchanges. Additionally, the ability to send and receive data in real-time facilitates more informed decision-making and timely responses to dynamic situations (Eurocontrol, 2023).

However, the implementation is not without challenges. Issues such as message latency, network congestion, and the need for robust cybersecurity measures must be addressed to ensure the reliability and security of communications. Furthermore, integrating datalink systems with existing avionics and ground-based infrastructure requires significant investment and coordination among various stakeholders (Eurocontrol, 2023).

2.3. ADS-C datalink

This research primarily focuses on the potential applications of ADS-C rather than CPDLC. Therefore, the concept of ADS-C will be explored in greater detail. To begin with, ADS-C uses several onboard systems of an aircraft to autonomously gather and transmit data such as location, altitude, speed, intent, and weather conditions. This information is compiled into reports and transmitted to either an Air Traffic Services Unit (ATSU) or an Aeronautical Operational Control (AOC) ground system (ICAO, 2017).

These reports are generated based on an ADS contract established by the ground system. The ADS contract specifies the kind of information required and the circumstances under which the aircraft should send these reports. While basic data is always included in the reports, other data is transmitted only if requested in the ADS contract. Moreover, the aircraft can send spontaneous ADS-C emergency reports to any ATSU with an established ADS contract (ICAO, 2017). A schematic overview of the operational context of ADS-C is given in Figure 2.2.

[2]FANS 1 and FANS A are developed by Boeing and Airbus respectively, but commonly known as FANS 1/A

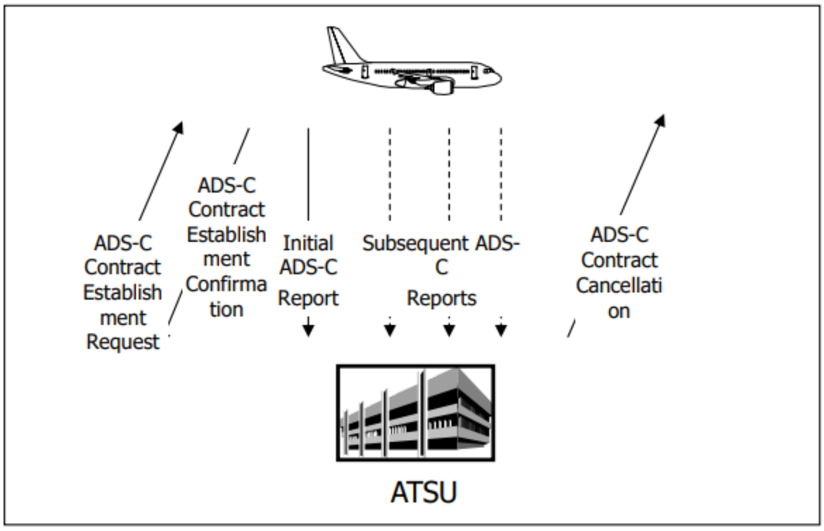

Figure 2.2: ADS-C operational context (EUROCAE, 2023)

Three basic contract categories exist for ADS-C (ICAO, 2017):

- **Periodic Contracts**: Define the reporting frequency at which the Flight Management System (FMS) must collect and transmit the specified requested information to the ground system. Only one periodic contract can be established between a particular ground system and a specific aircraft at any given moment.
- **Event Contracts**: Triggered by specific events (or series of events), such as Lateral Deviation Event, Vertical Rate Change Event, Level Range Change Event, and Waypoint Change Event. Only one event contract between a ground system and an aircraft can be established. However, this contract can contain multiple events.
- **Demand Contracts**: Single requests for an ADS-C report that includes specific information. Often referred to as a "one-shot" report, these contracts refresh ADS-C data and position information.

An aircraft can only have one active contract of a specific type with an ATSU at any given time. When an ATSU requests a periodic or event contract and the aircraft already has an active contract of that type, the new request will replace the existing contract. The acceptance of a new periodic or event contract implicitly cancels any ongoing contract of the same type. However, demand contracts are different; they are fulfilled by sending a single report, allowing multiple demand contracts to be established consecutively with the same aircraft (EUROCAE, 2023).

At the same time, an ATSU system can simultaneously establish multiple ADS contracts with a single aircraft, as long as they are different types (e.g., one periodic, one event-based, and multiple demand contracts). Furthermore, up to five ground systems can simultaneously have ADS contracts with a single aircraft (ICAO, 2017).

As previously mentioned, two standards support ADS-C: FANS 1/A and ATS B2. The latter contains more detailed information than FANS ADS-C, but they are related.

2.3.1. FANS 1/A

A FANS ADS-C report can consist of several groups. The Basic Group, included in each ADS-C report sent, contains the aircraft's current latitude, longitude, and altitude, along with a timestamp and a Figure of Merit (FOM) indicating the current level of navigation accuracy. Additionally, within the FANS ADS-C functionality, various "on-request" information groups can be added to the Basic Group for inclusion in an ADS-C report. These information groups must be requested by the ground system when creating the contract and include (ICAO, 2017):

- Flight identification group
- Earth reference group

- Air reference group
- Airframe identification group
- Meteorological group
- Predicted route group
- Fixed projected intent group
- Intermediate projected intent group

Intermediate Projected Intent (IPI) Group
A largely unknown group is the down-link trajectory called Intermediate Projected Intent (IPI) group. Up to 10 Trajectory Change Points (TCPs) can be added to the IPI group. To be eligible for inclusion in this group, a point must meet two criteria: it should be located between the current position and the fixed projected point in the Fixed Projected Intent (FPI) group, and it should be linked to a planned speed, altitude, or route change. The IPI group contains points generated by the FMS, such as the Top of Descent (ToD), and may not correspond to any specific waypoint in the flight plan (ICAO, 2017).

2.3.2. ATS B2 ADS-C
As with FANS, the Basic Group is always included in ATS B2 ADS-C, and several optional groups can be requested. Depending on the established contract, these optional groups may include air vector, ground vector, projected profile, meteorological data, RTA status data, TOA range, speed schedule profile, extended projected profile, planned final approach speed, holding information, runway occupancy data, and/or active VHF data.

Extended Predicted Profile (EPP)
A new trajectory definition called Extended Projected Profile (EPP), which is similar to the FANS IPI, was created by RTCA and EUROCAE. It extends and enhances the IPI group currently existing in FANS ADS-C. An EPP report contains the lateral and vertical TCPs ahead of the aircraft, detailing the trajectory within the report window in 4D. Each EPP also consists of the current gross mass and trajectory intent status. Each point includes position, altitude, waypoint name, estimated speed, time, vertical type, lateral type, and any posed constraints for that TCP. The specific lateral and vertical points included in the EPP report from any given aircraft depend on the design of its FMS (EUROCAE, 2023).

The EPP report can include the following lateral points (EUROCAE, 2023):

- **Fly-by or Fixed Radius Transition:** This includes each waypoint in the flight plan that requires either a fly-by or a fixed radius turn, regardless of any lateral offset.
- **Fly-over Transition:** This applies to waypoints in the flight plan that necessitate a fly-over transition.
- **Minimal or no track changes:** These are waypoints with little to no change in track, including along-track offset waypoints. The flight plan waypoint itself represents these points.
- **Radius-to-Fix (RF) Leg:** Each waypoint requiring an RF leg in the flight plan is included.
- **Lateral Offsets:** This includes points marking a lateral offset's start, end, or change.
- **Discontinuity:** Where a route discontinuity follows a waypoint.
- **Hold Entry:** Waypoints where the aircraft plans to enter a holding pattern.
- **Abeam:** Waypoints generated as the abeam projection of a waypoint no longer part of the route, typically used after a shortcut.
- **Along Track:** Waypoints are created based on a relative distance from another waypoint on the route.

The lateral waypoints that are most common are the 'Fly-by or Fixed Radius' and the 'Fly-Over'. These are depicted in Figure 2.3 and Figure 2.4.

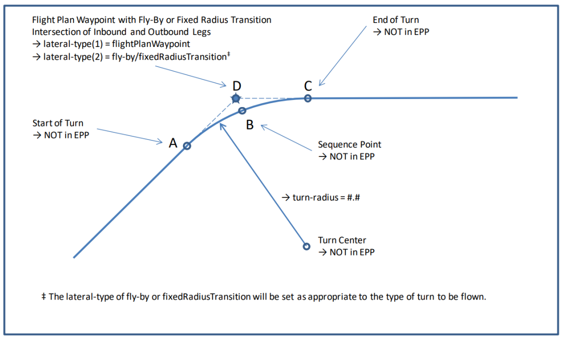

Figure 2.3: Fly-by and Fixed Radius turns (EUROCAE, 2023)

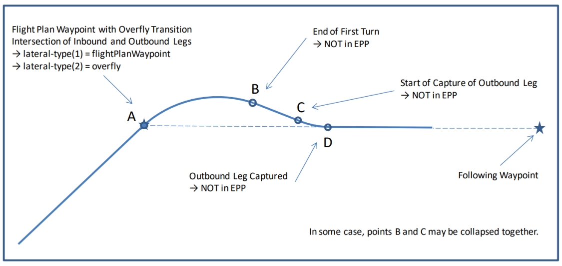

Figure 2.4: Fly-over turns (EUROCAE, 2023)

Regarding the vertical points, EPP can include the following points (EUROCAE, 2023):

- **Start of Climb:** This point marks the initiation of each climb segment from level flight or take-off.
- **Start of Decent:** This point signifies the beginning of each descent segment from level flight.
- **Top of Decent:** This indicates where the aircraft will start descending from its final cruise altitude towards the destination.
- **Top of Climb:** This point represents the end of the climb segment at the initial cruise altitude where the aircraft levels off.
- **Start of Level:** This point marks the altitude where the aircraft levels off on a specific altitude.
- **Start/End of Speed Change:** These points mark the beginning and end of any planned speed changes.
- **Crossover Level:** This point is where the speed target changes from Indicated Airspeed (IAS) to Mach during climb and from Mach to IAS during descent.
- **Speed Limit:** This point indicates where an altitude-based speed limit applies.

For this research, the most important points are Top of Descent (ToD), Start of Descent (SoD), Start/End of Speed Change (S/EOS) and Start of Level (SoL). Therefore, the first three points are illustrated in Figure 2.5 for extra clarification.

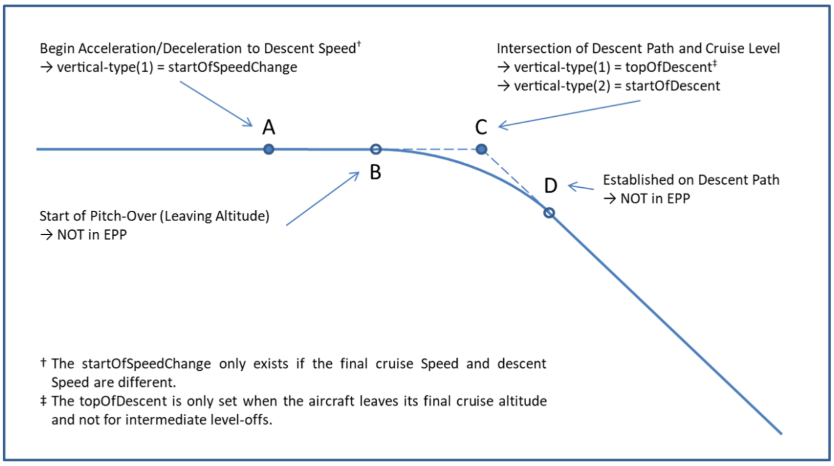

Figure 2.5: Start of Decent/Top of Descent (EUROCAE, 2023)

2.3.3. Comparison between FANS and ATS B2

A difference between FANS 1/A and ATS B2 lies in the type of network each uses. FANS 1/A operates on the ACARS network, while ATS B2 operates on the ATN. Additionally, ATS B2 includes a speed schedule profile in its reports, a feature not provided by FANS 1/A (de Gelder et al., 2022).

As IPI and EPP are closely related, discussing the similarities and differences is helpful. Bronsvoort et al. (2014) discusses this in Table 2.1. As shown in the table, the EPP contains more information than the IPI, which indicates that the EPP is a more extended version of the IPI. Furthermore, the EPP includes significantly more Trajectory Change Points (TCP) (128), compared to only 10 in the IPI, which suggests that the EPP looks further into the future than the IPI. Another important difference is the inclusion of gross mass data in the EPP. This information can help determine various performance parameters, such as descent/climb rate or fuel efficiency. Finally, the EPP presents the TCP using latitude and longitude coordinates, while the IPI depicts a TCP sequence through bearing and distance from its starting point or the previous TCP.

Table 2.1: IPI and EPP comparison (Bronsvoort et al., 2014)

Item		**Intermediate Projected Intent**	**Extended Predicted Profile**
General	Maximum number of trajectory change points	10	128
	Maximum look ahead time	0-255 mins	15-1200 mins
TCP Estimated State	TCP location	Yes (sequence of bearing and distance from start point)	Yes (Latitude and longitude)
	TCP altitude	Yes	Yes
	TCP time	Yes	Yes
	TCP speed	No	Yes
TCP Specification	TCP waypoint name (if appl.)	No	Yes
	TCP type specification	No	Yes
	Level change, e.g. Top of Climb (TOC) / Top of Descent (TOD)	Yes	Yes
	Lateral change	Yes	Yes
	Speed change start	Implementation dependant (at least one of two provided)	Yes
	Speed change end		Yes
	Waypoint	Depends if coincides with lateral/vertical/speed change	Yes
Turn Geometry	Fly-by turn radius	No	Yes
	Fly-over turn radius/radii	No	No
	Supports Radius to Fix (RF)legs	No	Yes
Additional Data	Gross mass	No	Yes

2.3.4. Applications and challenges of ADS-C

Due to the relatively new concept of ADS-C EPP, there has been limited research conducted recently on FANS, and specifically on the IPI. This is because the EPP represents an extension of the IPI, incorporating additional information, as illustrated in Table 2.1. Consequently, a clear concept of its use has not been properly defined, leading to limitations in its content and applications (Bronsvoort et al., 2016). Nevertheless, given that most wide-body aircraft are equipped with FANS, there remain numerous viable applications for the technology (MovingDot et al., 2014).

Applications of FANS ADS-C

Regarding the equipage rate of FANS 1/A ADS-C, in January 2023, according to Eurocontrol flight plan data, 32% (849 in absolute terms) of aircraft flying to and from Schiphol Airport were equipped with FANS 1/A ADS-C capabilities. This corresponds to roughly 21% of the total number of flights during that month (de Gelder et al., 2022). However, between 4:00 AM and 6:30 AM (local time), there is a significant rise in the use of ADS-C equipment by arriving aircraft, reaching up to an 80% increase. This increase is mainly due to the arrival of many intercontinental wide-body aircraft. Additionally, the amount of aircraft equipped with ADS-C is a lot higher in the United States, where also narrow-body aircraft are equipped with FANS ADS-C (MovingDot et al., 2014).

Several applications of FANS ADS-C are discussed in the report authored by MovingDot et al. (2014). For example, the IPI can provide the predicted altitude for each TCP, offering relevant data for specific coordination points at sector boundaries or the IAF. A potential benefit for ACC ATCOs is the improvement of situational awareness regarding the intentions of arriving aircraft. Furthermore, ADS-C data can assist in verifying the selection of the correct runway, i.e., if the correct frequency for the Instrument Landing System (ILS) has been selected. This verification is possible through the FPI group of FANS because the final waypoint for each flight corresponds to the runway. As a result, this might eliminate the need for voice confirmation of the correct

ILS frequency. For APP ATCOs, an advantage would be the reduction of workload, particularly in scenarios involving parallel landings.

Other research indicates that FANS ADS-C data can improve ground-based trajectory predictions laterally and longitudinally. However, with the more advanced standard of ADS-C, it is expected that these kinds of applications will primarily be used with the ATS B2 ADS-C data (Bronsvoort et al., 2013).

Applications of ATS B2 ADS-C

Since ATS B2 ADS-C is a more recent and comprehensive standard than FANS ADS-C, most of the applications of FANS ADS-C are also applicable to ATS B2. However, several studies have explored the applications of, specifically, EPP. For instance, Bronsvoort et al. (2016) and Sosovicka et al. (2015) suggest that the EPP, instead of being directly used for its reference trajectory, can be utilized to derive other aircraft performance parameters. This approach uses the data from the EPP derived from the aircraft's FMS, which is the most accurate source of intent parameters. Consequently, it can improve the accuracy of the ground system's Trajectory Predictor (TP). The types of data that can be shared include speed profiles, aircraft mass, performance metrics, and numerous other parameters from the EPP as discussed in Table 2.1.

The SESAR3 Joint Undertaking recently published a new demonstration report as part of the ADSCENSIO project (PJ38). The project's objectives are cited as follows (DSNA et al., 2023): "The objectives were to demonstrate improvements of ATM operations enabled by the use of ADS-C data, with the support of the suitable technical infrastructure.". Several ANSPs and other large organizations, such as Airbus and Honeywell, participated in this demonstration. The report discusses several interesting applications.

For example, according to DSNA et al. (2023), Conflict Detection & Resolution (CD&R) can be improved by using ADS-C EPP data, which will improve the safety. This is particularly relevant with the recent introduction of TBO, where conflict detection becomes a key function to ensure air transport safety. In TBO, aircraft have greater flexibility in trajectory planning and bear more responsibility for maintaining separation. Research by Hao et al., 2018 already focuses on conflict detection within TBO contexts. Furthermore, CD&R tools can be fine-tuned using EPP mass and speed schedule data and when aircraft performance models are refined in TP tools, as demonstrated by Air Traffic Controllers (ATCOs) in DSNA et al., 2023, it can lead to improvements in CD&R. Additionally, during a conversation with an ATCO from LVNL, Stefan van der Loos mentioned that conflict detection via ADS-C, using only intent data, was less interesting right now. He explained that if the ADS-C trajectory data shows two aircraft crossing each other's flight paths at a minimal vertical or lateral distance, then this data must be 100% accurate for effective conflict detection. This was also acknowledged by ATCOs from the demonstration exercises in DSNA et al. (2023). The ATCO prefers to be on the safe side and will likely intervene to increase their separation (van der Loos S., Personal communication, February 7, 2024).

Another application discussed in DSNA et al. (2023) is using ADS-C intent data to resolve airspace discrepancies. For instance, in cases where restricted areas become active, EPP data can demonstrate that an aircraft will exit the restricted area promptly, thereby enhancing safety. Additionally, this data can improve 2D conformance monitoring by visualizing discrepancies between the 2D ground trajectory and the EPP.

Challenges of ADS-C EPP

Despite the many different use cases for EPP and potential benefits, the message standard (ATS B2) is not without its limitations (Guerreiro and Underwood, 2018). Previous research indicates that there are still challenges that need to be addressed to use the EPP directly as the reference trajectory to be used by ANSPs Decision Support Tools (DSTs). Klooster et al. (2010) discuss several additional reasons why the ATC ground system should not directly adopt the airborne predicted trajectory. For instance, replacing the trajectory calculated on the ground with the one predicted in the air might cause instability and discrepancies because of the varying methods used in computing these trajectories.

Additionally, as indicated in Table 2.1, the EPP includes information on the radius of fly-by turns and supports Radius-to-Fix (RF) legs. However, it lacks support for the geometry of fly-over turns. This omission can lead to inaccuracies in trajectory predictions, as turn modeling is listed by Mondoloni and Bayraktutar (2005) as one of the high-impact factors for prediction accuracy. Bronsvoort et al. (2014) also highlights the impact of the absence of information on the radius of fly-over turns. In cases generating lateral trajectories for fly-over waypoints, assumptions must be made. These assumptions can result in inaccuracies in both lateral and longitudinal trajectory predictions. Mondoloni and Bayraktutar (2005) include another high-impact factor to their list affecting prediction accuracy, namely the lack of aircraft weight. Although the EPP contains the aircraft's current gross mass when the reference trajectory for the EPP message was established, it does not include predictions on fuel consumption, resulting in possible inaccurate aircraft weight.

Furthermore, during the development of the EPP, various decisions were made to minimize complexity and bandwidth usage. One such decision was excluding temperature and wind forecasts from the EPP report, which the FMS uses for trajectory predictions. Additionally, real-time data on wind and temperature conditions that the aircraft encounters during trajectory calculations are not captured in the EPP. This factor, identified by Mondoloni and Bayraktutar (2005), influences the accuracy of trajectory predictions.

2.4. Dutch Airspace Redesign Program (DARP)

The DARP is a collaborative initiative involving the Ministry of Infrastructure and Water Management, the Ministry of Defence, the Royal Netherlands Air Force, LVNL, and MUAC. The primary aim of the program is to enhance the efficiency, safety, and environmental sustainability of Dutch airspace to meet future demands (of Infrastructure and Management, 2022).

Challenges and goals
Despite its potential benefits, DARP faces several significant challenges. One primary issue is the integration of civil and military airspace to ensure both sectors operate efficiently and safely. This integration requires detailed coordination and planning to balance the diverse requirements of different airspace users (NLR and RoyalHaskoningDHV, 2021). The program also seeks to accommodate the increasing use of unmanned aerial vehicles (UAVs), which adds a layer of complexity to air traffic management (of Infrastructure and Management, 2021).

Environmental impact
Reducing environmental impact is a key objective of DARP. The program aims to implement shorter, more direct flight routes and optimize continuous climb and descent procedures. These changes are expected to reduce CO2 emissions and noise pollution. However, the effectiveness of these measures relies heavily on precise coordination and the development of new ATC procedures. Continuous monitoring and adjustments based on real-world data are essential to achieving the desired environmental benefits (NLR and RoyalHaskoningDHV, 2021).

Airspace restructuring
Restructuring the airspace to facilitate more direct routes to major airports such as Schiphol, Rotterdam-The Hague, and Lelystad presents logistical challenges. One of the major aspects of this restructuring involves the realignment of the east and southeast sections of the Dutch airspace. This realignment will enable the implementation of a fourth Initial Approach Fix (IAF) for both Schiphol and Rotterdam-The Hague airports, located to the southeast of Schiphol. This development aims to enhance the efficiency and accessibility of these airports, reducing congestion and improving flight. The transition to the new airspace structure must be managed carefully to prevent disruptions and ensure a smooth implementation process (of Infrastructure and Management, 2022).

Military collaboration
The program also involves expanding the northern military training zone and integrating it into a cross-border Dutch-German area. This expansion aims to free up airspace in the southeast for civil aviation, thereby improving overall efficiency. Successful implementation of this initiative requires effective international cooperation and agreement on airspace usage protocols between Dutch and German air traffic control authorities (of Infrastructure and Management, 2022). This expansion is illustrated in Figure 2.6.

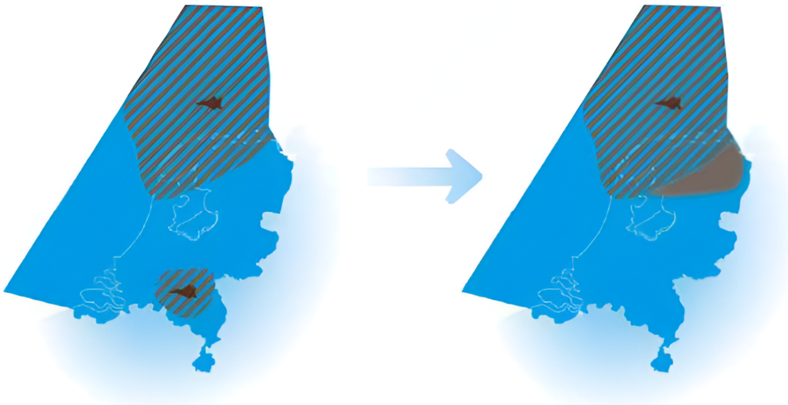

Figure 2.6: Relocation/expansion of military training area (NLR and RoyalHaskoningDHV, 2021)

Implementation timeline
DARP is being implemented in phases, with initial steps starting in 2023. Detailed plans are developed with stakeholders, including local communities, government bodies, and environmental groups. This phased approach ensures that the necessary adjustments can be made based on ongoing feedback and operational experiences (NLR and RoyalHaskoningDHV, 2021).

2.5. Thematic analysis

This section presents the findings from the thematic analysis conducted on the informal conversations and more formal interviews with relevant stakeholders, such as air traffic controllers and procedure designers. The aim was to identify key themes regarding current procedural standards, technological adaption, and specific simulation scenarios.

The notes from the informal conversations and a snippet of the transcribed interview are presented in Appendix B. Note that the conversations with Jonah and Danny (Appendix B.1), Stefan (Appendix B.2), and the interview with Tristan (Appendix B.3) were conducted in Dutch, and the initial notes/transcriptions have been translated into English.

2.5.1. Methodology

The study conducted qualitative interviews with four individuals, combining two into a single conversation. Approval for using the information gathered from the interviews was obtained, ensuring confidentiality and informed consent. Thematic analysis was selected for its flexibility and depth, facilitating a thorough data exploration. The study adheres to Braun and Clarke (2006) six-phase method, from familiarizing with the data to defining and naming themes.

2.5.2. Findings

Theme 1: Operational Challenges and Efficiency
This theme highlighted the complexities and constraints faced by air traffic management in the Dutch FIR. Interviewees mentioned and acknowledged the limited influence over the Top of Descent due to airspace constraints, affecting the efficiency of the Dutch air traffic control. For example, one interviewee noted, "Due to the relatively small size of the Dutch FIR, the ToD for aircraft often lies within other FIRs..." Additionally, the desire for earlier and more accurate data to facilitate efficient planning was a recurring point, emphasizing the need for improved communication and data sharing among neighboring FIRs. However, it was explicitly stated that the reliability of the shared data is paramount.

Theme 2: Strategies for Optimization
Strategies for optimization, such as adjusting aircraft speeds for cost optimization, were discussed. The discussion around adjusting aircraft speeds according to airline cost indices for economic efficiency illustrates a practical approach to managing air traffic flow and reducing congestion. One interviewee mentioned: "If

one aircraft adjusts its speed to align with its airline's cost index for economic efficiency, and another aircraft selects a different speed to achieve its cost optimization, this speed variance can naturally prioritize aircraft sequencing.". This theme also reflects on the potential benefits of implementing advanced scheduling and routing technologies to prioritize aircraft sequencing and enhance airspace utilization.

Theme 3: Technological Adaptation and Integration
The potential of datalink technology and ADS-C for improving operational efficiency was a recurring topic. This theme covers the challenges of incorporating new technologies into existing systems and anticipating future advancements, such as the widespread adoption of ADS-C datalink technology for improved operational efficiency and safety. The interviewees highlighted the necessity for additional equipment, like extra screens to accommodate the extra features of datalink technology, as a practical solution.

Theme 4: Sustainability and Environmental Impact
A theme that emerged from the analysis focuses on the environmental implications of air traffic operations. This theme covers the design and implementation of flight procedures that support sustainable operations, such as Continuous Descent Operations (CDOs) and Required Navigation Performance (RNP) approaches, aimed at reducing fuel consumption and minimizing emissions. An interviewee mentioned: "In the context of airspace revision, one of the main objectives is to make operations at Schiphol more sustainable. This directly translates into the need to enable more Continuous Descent Operations.". The discussion highlights a growing awareness within ATM about the importance of environmental sustainability and the need for procedures that balance operational efficiency with environmental impact.

Theme 5: Key Performance Indicators in ATM
This theme captures the conversation around defining and using Key Performance Indicators (KPIs) to measure certain aspects of air traffic operations. One of the interviewees discussed that many external factors influence airspace capacity; therefore, it is difficult to determine the exact capacity. However, assumptions can be made to make it easier to measure. Furthermore, an interviewee highlighted: "Environmental impact directly correlates with efficiency in flying, where more efficient flight paths lead to reduced emissions.". It is important to take this into account when defining the KPIs.

Theme 6: ATM simulation scenarios
The final theme that has been identified is the simulation scenarios, which focus on the use of simulations to forecast, evaluate, and optimize air traffic control procedures and datalink technology integration. Several interesting views emerged from the interviews for specific scenarios to be tested in simulations. For example, one interviewee noted: "Simulation scenarios that are of interest include monitoring outbound speeds and managing inbound congestion, a process referred to as "bunging", which involves adjusting aircraft speeds or routes to ensure efficient spacing for landing sequences.". A way to validate the accuracy of the datalink data, an interviewee mentioned: "Monitoring times and altitudes at EPP waypoints against radar data presents an interesting opportunity for validating and enhancing the accuracy of this data.".

Another example of a specific scenario from an interviewee was: "... the intersecting inbound and outbound paths that are critical to us... Without ADS-C information, we would be tempted to give instructions to level off, leading to more noise and fuel consumption as aircraft are in the air longer. With ADS-C information, we might not need to give such instructions or could give a different instruction with a different effect on noise, fuel consumption, and track miles.".

Finally, an interviewee mentioned an interesting scenario in which a combination of RNP and ILS approaches are flown. With RNP approaches, the alignment to the runway can be more direct, potentially leading to conflicts with aircraft approaching via ILS. However, if ADS-C data can confirm enough separation between aircraft due to their detailed trajectory information, this presents an interesting use case.

2.5.3. Conclusion

This thematic analysis has highlighted the different perspectives of individuals on the challenges and opportunities related to datalink within the Dutch FIR. It contributes to a deeper understanding of actual use cases and interesting KPIs and scenarios to further develop for this research.

3
Airspace procedures

Airspace and procedure design refers to the structured planning and configuration of airspace and the flight procedures used to ensure safe, efficient, and effective use of the airspace by all aircraft. This multidisciplinary process involves a range of considerations, including safety, environmental impact, and the operational requirements of civil and military aviation. The goal is to optimize airspace to meet current and future demands, taking into account the evolving nature of aircraft technologies, traffic volumes, and operational practices (SKYbrary, 2024a).

This chapter discusses the current procedures within the lower airspace of the Dutch FIR. However, to achieve a thorough overview, a general description of the multi-layered airspace structure of the Netherlands, including its various sectors, is presented. Furthermore, general and special flight procedures related to airport operations, such as departing and arriving aircraft, are explained. Finally, the separation minima are discussed.

3.1. Airspace structure

This section explains how the structure of the Dutch airspace and around Schiphol is constructed.

3.1.1. Airspace classes

The Dutch airspace is composed of both controlled and uncontrolled airspace. It is classified into different classes (e.g., A through G). It adheres to ICAO standards for airspace classification based on the level of service provided and the requirements for entry. The classification system is designed to ensure safe and efficient use of airspace by different types of air traffic. A schematic overview of the different classes is presented in Figure 3.1.

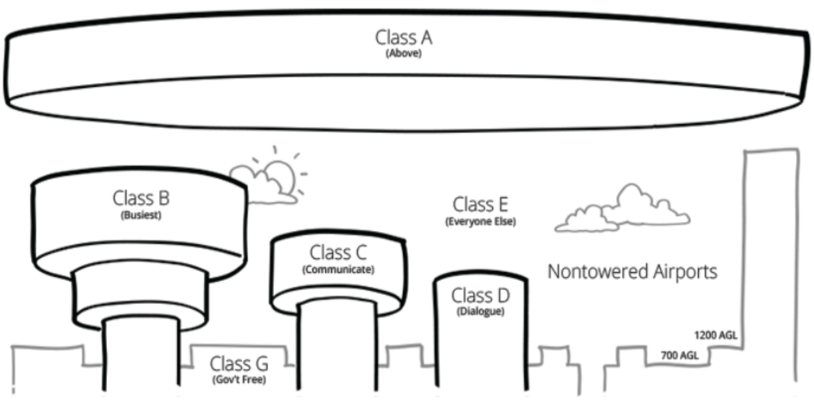

Figure 3.1: Airspace classes (Hoekstra and Ellerbroek, 2023)

The different classes, according to ICAO (2018), are explained as follows:

Class A airspace within the Dutch FIR is dedicated exclusively to IFR) operations. It guarantees the highest level of ATC service by providing full separation from all aircraft, ensuring maximal safety for high-density air traffic areas. Entry into this airspace requires an ATC clearance.

Despite allowing IFR, Special Visual Flight Rules (SVFR), and Visual Flight Rules (VFR) flights, Class B airspace maintains a strict control environment similar to Class A and provides full ATC services. In this case, IFR flights are guaranteed to be kept apart from all other traffic, while VFR flights are kept apart from IFR operations.

Class C introduces a mix of IFR, Special Visual Flight Rules (SVFR), and Visual Flight Rules (VFR) operations, with ATC providing separation for IFR flights and traffic information for VFR flights. IFR flight need ATC clearance, whereas VFR flights must establish two-way radio communication with ATC before entry, ensuring coordinated use of the airspace.

In class D, ATC services are available for IFR, SVFR, and VFR operations, and all types of flights are allowed. IFR flights are seperated from other IFR flights and receive traffic information about VFR flights, while VFR flights receive traffic information about all other flights.

Class E is characterized by its provision of ATC services primarily for separating IFR and SVFR flights, with VFR operations permitted without explicit ATC separation. This class represents more permissive airspace, where IFR flights receive clearance, emphasizing the importance of self-separation and situational awareness for VFR pilots.

In Class F airspace, ATC provides advisory services rather than active control, offering traffic information and alerting services to both IFR and VFR flights. This advisory capacity supports pilots in making informed decisions, fostering a cooperative airspace environment without mandatory ATC clearance.

Class G is the most unrestricted airspace within the Dutch FIR, where ATC services are limited to flight information and alerting services. There are no clearance requirements, embodying the "see and avoid" principle that places the onus on pilots to maintain safety while maximizing freedom of movement.

3.1.2. Airspace around Schiphol

The Dutch airspace around Schiphol Airport, one of Europe's busiest airports, is structured to ensure the safety and efficiency of air traffic. It comprises several types of airspace as depicted in Figure 3.2, including Terminal Manoeuvring Area (TMA), Control Zone (CTR), Control Area (CTA), and Upper Control Area (UTA), each serving different purposes.

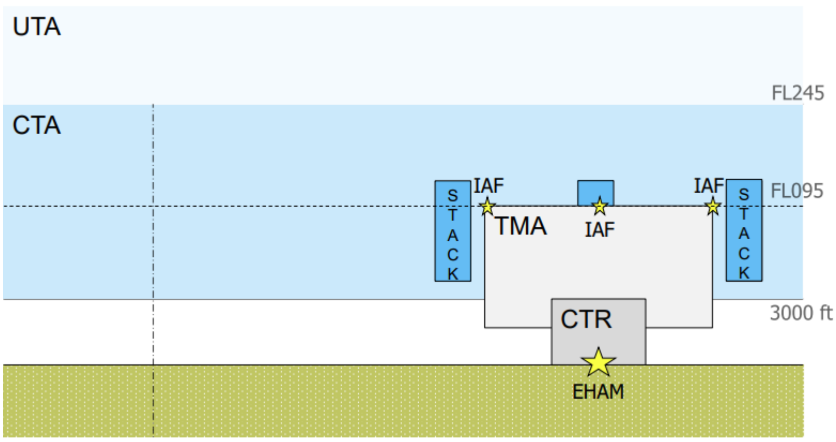

Figure 3.2: Airspace around Schiphol (Hoekstra and Ellerbroek, 2023)

The report explains the different areas and zones, including the authorities responsible for each zone (Ministry of Infrastructure and the Environment and Ministry of Defence, 2011).

First, the CTR is a controlled airspace extending around Schiphol, designed to protect departing and arriving traffic around the airport from other airspace users. It is a defined volume of airspace that usually extends from the surface up to a specified upper limit. Traffic within the CTR is separated by TWR Control, responsible for final approaches, take-off clearances, and ground control.

Furthermore, the TMA is airspace intended to protect aircraft climbing from or descending towards the airport. It surrounds the airport and is controlled by APP. The TMA is designed to ensure aircraft are properly sequenced and separated while minimizing conflicts and efficiently managing traffic flow.

The airspace surrounding the TMA is called the CTA. Since the Schiphol TMA is smaller than other major airports, the Dutch CTA also receives a lot of climbing and descending traffic. The CTA of the Netherlands has been divided into five possible sectors. These sectors are illustrated in Figure 3.3. Depending on traffic density and whether the sectors are combined, an air traffic controller of ACC is in charge of all incoming and outgoing aircraft. The purpose of the CTA is to protect overflights on the so-called ATS routes, which are aerial "highways".

Additionally, special traffic zones may be established if (temporary) prohibitions or restrictions are required to accommodate operations that cannot be integrated with civil aviation. There is a differentiation between what is referred to as restricted areas (EHP), danger areas (EHD), and prohibited areas (EHR). These (temporary) restricted or forbidden areas are often activated when military aircraft operations occur. These military exercise areas are above the Waddenzee, Twente, and the South-East of the Netherlands (Figure 3.4).

Figure 3.3: Schiphol TMA and CTA sectors (Ministry of Infrastructure and the Environment and Ministry of Defence, 2011)

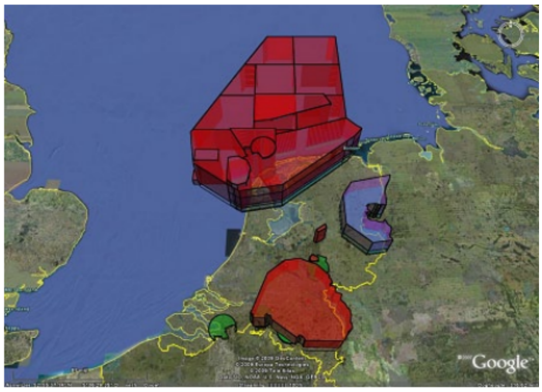

Figure 3.4: Location of military exercise areas (Ministry of Infrastructure and the Environment and Ministry of Defence, 2011)

The final airspace defined is the UTA. The UTA is airspace designated in the upper levels, above the CTA, to manage high-level en-route air traffic. It is designed to ensure the safe and efficient movement of aircraft flying at higher altitudes, typically above FL245, also referred to as upper airspace. In the UTA, UAC, such as MUAC, separates all aircraft to prevent collisions and ensure smooth traffic flow.

3.2. Standard flight procedures

Standard flight procedures in the Dutch airspace, especially around major airports like Schiphol, are designed to ensure safety, efficiency, minimal environmental impact, and noise abatement. These procedures involve SIDs and STARs, which are predetermined flight paths that aircraft follow during the departure and arrival phases of the flight. To initiate either procedure, the aircraft must receive clearance to proceed with the relevant SID or STAR.

3.2.1. SIDs

SIDs are predefined routes that departing aircraft follow from the runway until they reach a specified point, typically on an ATS route, where they can safely transition to en-route operations. These procedures are designed to ensure that aircraft are separated from each other and arriving traffic, and minimize noise pollution in densely populated areas around airports. Furthermore, they aim to improve the efficiency of ATC by standardizing routes (ICAO, 2016b).

3.2.2. STARs

STARs are the arrival counterpart to SIDs, providing predefined routes for aircraft to follow from the en-route phase down to an IAF near the destination airport. STARs are designed to streamline the flow of arriving aircraft into a manageable sequence for ATC, ensuring safe separation between arriving and departing flights, as well as between aircraft on parallel arrival paths. Additionally, by standardizing arrival procedures, STARs aim to reduce the workload for pilots and controllers, facilitating a smoother and safer approach into airports (ICAO, 2016b).

3.2.3. Holding areas

Special procedures, such as holding, are an essential part of air traffic management, providing a method for controlling aircraft when they cannot proceed directly to their destination or next phase of flight. These procedures are common in busy airspace to manage traffic flow, deal with congestion, or await further instructions due to various reasons such as weather, operational delays, or emergencies.

Schiphol uses three holding areas, each associated with distinct IAFs and named according to their geographical positions or navigational aids. Illustrated in Figure 3.5, these holding areas are situated at the edge of the TMA, specifically at ARTIP (close to Lelystad), RIVER (near Rotterdam), and SUGOL (above the North Sea). The term 'Wachtgebied' is the Dutch translation for 'holding area' (Ministry of Infrastructure and the Environment and Ministry of Defence, 2011).

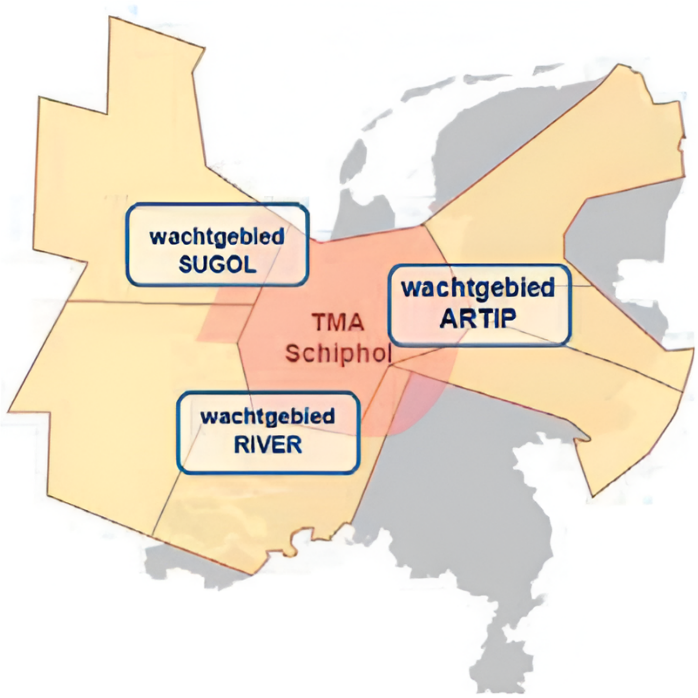

Figure 3.5: Holding area's of the Netherlands(Ministry of Infrastructure and the Environment and Ministry of Defence, 2011)

3.2.4. ILS and RNP approaches

In aviation, multiple approach types are possible to direct aircraft during the arrival phase of a flight to the runway. Two are: Required Navigation Performance (RNP) approaches and Instrument Landing System (ILS) approaches. Despite using distinct technology and concepts, both systems are intended to provide safe and effective navigation, especially in complex airspace or during adverse weather.

ILS

ILS is a precision approach aid that gives the pilots both vertical and horizontal guidance when an aircraft approaches a runway. It consists of two main components: the glide slope, which provides vertical guidance to ensure the aircraft descends at the correct angle (usually 3 degrees) to reach the runway at the appropriate touchdown point, and the localizer, which provides lateral guidance to guarantee the aircraft is aligned with the runway center line. ILS approaches are widely used due to their high level of accuracy and reliability, especially under low visibility conditions (SKYbrary, 2024b.)

RNP

RNP approaches, part of the Performance Based Navigation (PBN) framework, require aircraft to use onboard navigation systems that can accurately calculate their position. RNP approaches specify a navigational accuracy requirement that needs to be maintained throughout the approach path. Unlike ILS, which depends on ground-based navigation aids, RNP uses satellite navigation systems. This makes it possible to create more flexible approach paths, such as curved ones that may be optimized for noise abatement, fuel efficiency, and avoid obstacles or terrain (ICAO, 2023).

ICAO (2023) specifies seven RNP navigation specifications: RNP4, RNP2, RNP1, Advanced RNP, RNP APCH, RNP AR APCH, and RNP 0.3. Applications requiring remote continental and oceanic navigation use RNP 4. Applications requiring en-route continental and en-route oceanic remote navigation use RNP 2. RNP 1 is for navigation applications related to arrival, initial, intermediate, and missed approaches and departure. Advanced RNP is used for navigation during all flight phases. During the approach phase of flight, RNP APCH and RNP AR (authorization required) APCH are utilized for navigational purposes. RNP 0.3 applies specifically to helicopter operations and covers the en route continental, arrival, departure, and approach stages of flight (except final approach) (ICAO, 2023).

Mixed approach operations on a single runway

In this context, using both ILS and RNP approaches at an airport for the same runway is referred to as mixed approach operations. This combination can optimize airport and airspace capacity and flexibility by enabling aircraft with different levels of navigational capability to select the most suitable approach type. For instance, to preserve efficiency and safety during peak traffic times or in variable weather conditions, an airport might use both RNP approaches for aircraft capable of flying them and ILS for aircraft that require or prefer it. However, mixed operations require careful air traffic control to maintain separation and control over the varying approach speeds and paths of approaching aircraft (Amai and Matsuoka, 2015).

Research has already been conducted on mixed operations on a single runway at an airport without parallel runways (Amai and Matsuoka, 2015). The paper describes a real-time ATC simulation experiment designed to examine the feasibility of mixed operations (RNP AR and ILS procedures) involving quasi-controllers—individuals acting as air traffic controllers—and quasi-pilots. Additionally, it explains the difficulties associated with mixed operations, as depicted in Figure 3.6. The concept of mixed operations, as described by Amai and Matsuoka (2015), is illustrated in Figure 3.7. Procedures 1 and 3 use an ILS approach, whereas procedure 2 flies a RNP approach (curved).

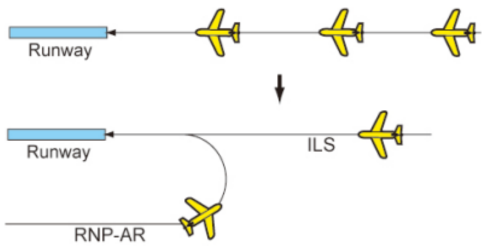

Figure 3.6: Difficulty of air traffic control (Amai and Matsuoka, 2015)

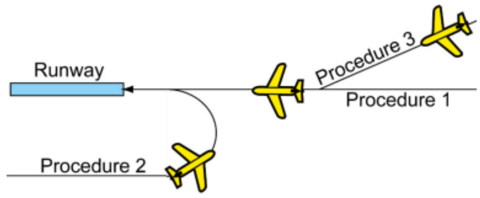

Figure 3.7: Concept of mixed operations (Amai and Matsuoka, 2015)

3.3. Separation minima

The primary objective of ATC, and aviation as a whole, is safety; therefore, maintaining safe separation between aircraft in controlled airspace at all times is paramount. This encompasses vertical, horizontal, and wake turbulence separation. Different separation minima are applicable during various phases of the flight.

3.3.1. Vertical and horizontal separation

As for vertical separation minima (VSM), the minimum separation is 300 meters (1000 feet) below FL290 and 600 meters (2000 feet) above this level. However, Reduced Vertical Separation Minima (RVSM) may apply above FL290, in which case the separation is 300 meters (1000 feet) up to FL410 (ICAO, 2016b).

Horizontal separation is categorized into lateral and longitudinal separation. Lateral separation is achieved when aircraft send position reports, such as ADS-C messages, confirming that the two aircraft are in different geographic locations. This can also be accomplished by requiring aircraft to fly on predetermined tracks that maintain a minimum angular difference, which is determined by the type of navigation aid used. The two trajectories must diverge, with at least one aircraft being at least 15 NM from the navigation aid. Longitudinal separation ensures that two aircraft maintain a minimum distance from each other. For aircraft flying the same or diverging paths, this can be achieved through position reporting and ensuring that the preceding aircraft does not overtake the succeeding aircraft by maintaining a lower or equal speed (ICAO, 2016b).

When ATS surveillance systems, such as radar, ADS-B, or MLAT, are used, the minimum horizontal separation is 5 NM (9.3 km). However, at locations where system capabilities allow, this minimum separation can be reduced to 3 NM (5.6 km), which is the case inside the TMA. Furthermore, under certain conditions, it can be further reduced to 2.5 NM (4.6 km) when succeeding aircraft are established on the same final approach track within 10 NM (18.6 km) of the runway threshold (ICAO, 2016b).

3.3.2. Wake turbulence separation

When two aircraft are on the same track, the preceding aircraft can encounter turbulence caused by the succeeding aircraft, especially when a heavier aircraft is ahead of a lighter one. This turbulence, known as wake turbulence, can potentially lead to a loss of control and is considered highly dangerous. Therefore, the separation prescribed by ATC may not necessarily be sufficient to prevent such incidents. Consequently, additional separation distances, based on the Maximum Take-Off Mass (MTOM) of the aircraft, must be maintained between certain aircraft categories to mitigate this risk.

Aircraft can be categorized in four Wake Turbulence Categories (WTC) (ICAO, 2016b):

- **J (Super)**[1]: Aircraft types in the order of 560,000 kg MTOM
- **H (Heavy)**: Aircraft types of 136,000 kg or more (except category J)
- **M (Medium)**: Aircraft types less than 136,000 kg and more than 7,000 kg
- **L (Light)**: Aircraft types less than 7,000 kg.

[1] A380 is the only type in this category

The wake turbulence separation minima are presented in Table 3.1. The minimum distance is primarily used when radar separates arriving and departing traffic. However, since only a few airports use radar separation for takeoff and initial climb, it is typical for the separation of arriving aircraft to be based on distance. For departing aircraft, on the other hand, the separation is typically based on time ICAO, 2016b).

Table 3.1: Minimum separation distances and time (ICAO, 2016b)

Preceding Aircraft	**Following Aircraft**	**Minimum Distance**	**Minimum Time**
Super	Heavy	6.0 NM	2 min
Super	Medium	7.0 NM	3 min
Super	Light	8.0 NM	3 min
Heavy	Heavy	4.0 NM	3 min
Heavy	Medium	5.0 NM	2 min
Heavy	Light	6,0 NM	2 min
Medium	Light	5,0 NM	2 min

3.3.3. Wake-RECAT

Wake RECAT (Wake Turbulence Re-categorization) is a program designed to enhance the efficiency and capacity of airport operations by refining the way aircraft are categorized in relation to wake turbulence. The traditional wake turbulence categorization, described above, while effective, does not fully account for the nuances of how different aircraft types produce and respond to wake turbulence. It takes into account not just the mass but also the aerodynamic characteristics of aircraft to better understand the wake turbulence they generate. By doing so, Wake RECAT enables closer and safer spacing between certain types of aircraft, thus increasing airport capacity and reducing delays without compromising safety (Rooseleer and Treve, 2018).

Table 3.2 illustrates the required separation distance under the RECAT program. An empty field indicates the minimum radar separation, which is equal to 2.5 NM (ICAO, 2016b). For arrivals and possibly departures, the separation is specified by distance.

Table 3.2: RECAT-EU scheme distance (Rooseleer and Treve, 2018)

Follower		**'Super heavy'**	**'Upper heavy'**	**'Lower heavy'**	**'Upper medium**	**'Lower medium'**	**'Light'**
Leader/		**A**	**B**	**C**	**D**	**E**	**F**
'Super heavy'	**A**	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
'Upper heavy'	**B**		3 NM	4 NM	4 NM	5 NM	7 NM
'Lower heavy'	**C**			3 NM	3 NM	4 NM	6 NM
'Upper medium	**D**						5 NM
'Lower medium'	**E**						4 NM
'Light'	**F**						3 NM

Table 3.3 shows the required time minima according to the RECAT program. For departing aircraft, the separation is given by time.

Table 3.3: RECAT-EU scheme time (Rooseleer and Treve, 2018)

Follower		**’Super heavy’**	**’Upper heavy’**	**’Lower heavy’**	**’Upper medium**	**’Lower medium’**	**’Light’**
Leader/		**A**	**B**	**C**	**D**	**E**	**F**
’Super heavy’	**A**		100s	120s	140s	160s	180s
’Upper heavy’	**B**				100s	120s	140s
’Lower heavy’	**C**				80s	100s	120s
’Upper medium	**D**						100s
’Lower medium’	**E**						100s
’Light’	**F**						80s

3.4. ATC procedures for Conflict Detection and Resolution

Effective air traffic control is essential for maintaining safe and efficient operations within controlled airspace. A crucial aspect of ATC responsibilities includes detecting and resolving potential conflicts between aircraft. Conflict detection and resolution (CD&R) involve a series of procedures and technologies designed to predict and mitigate situations where two or more aircraft may come too close to one another, potentially leading to hazardous conditions.

3.4.1. Conflict detection

Conflict detection is the process by which ATC identifies potential loss of separation between aircraft. It relies on various tools and methodologies to ensure safe and efficient air traffic management.

Surveillance systems

Surveillance systems are an essential component of conflict detection. Primary and secondary radar systems provide continuous updates on aircraft positions, allowing controllers to monitor and detect conflicts in real time. Primary radar detects aircraft’s location by reflecting radio waves off their surfaces. In contrast, secondary radar relies on transponders onboard aircraft to provide additional information such as altitude and identification. In addition to radar, Automatic Dependent Surveillance - Broadcast (ADS-B) significantly enhances situational awareness. ADS-B broadcasts an aircraft’s GPS position, velocity, and other data to ground stations and other nearby aircraft, providing highly accurate and frequent updates essential for timely conflict detection (Thales Air Systems, 2014).

Flight Data Processing Systems (FDPS)

FDPS plays a critical role in conflict detection by integrating data from various sources, including flight plans, radar, and ADS-B. These systems use algorithms to analyze aircraft trajectories and predict where conflicts may occur. By providing early warnings to controllers, FDPS enables proactive management of potential conflicts, ensuring appropriate measures can be taken well in advance.

Conflict prediction tools

Conflict prediction tools are integral to conflict detection processes, offering different time frames for alerting controllers to potential issues. Medium Term Conflict Detection (MTCD) systems predict potential conflicts up to 20 minutes in advance. These tools analyze aircraft trajectories, considering current flight plans and possible changes in course or altitude, thereby giving controllers ample time to take corrective action (EUROCONTROL, 2017). On the other hand, Short Term Conflict Alert (STCA) systems provide immediate warnings of potential conflicts within a shorter time frame, typically up to two minutes. STCA is designed to assist controllers in identifying urgent conflicts that require immediate resolution, ensuring prompt and effective interventions to maintain safe separation (EUROCONTROL, 2007).

3.4.2. Conflict resolution

Once a potential conflict is detected, ATC must implement resolution procedures to maintain safe separation. These procedures can include adjustments to altitude, speed, and flight paths, known as vectoring.

Altitude changes
Controllers may instruct one or both aircraft to climb or descend to different flight levels to maintain vertical separation. As discussed in Section 3.3, the standard vertical separation minimum is 1000 feet below FL290 and 2000 feet at or above FL290, except in Reduced Vertical Separation Minima (RVSM) airspace, where the minimum separation is 1000 feet up to FL410. By altering the altitude of one or more aircraft, controllers can maintain sufficient vertical distance, thus preventing potential conflicts.

A rule known as the '60/70 rule' is a specific vertical separation standard used in controlled airspace and involves maintaining specific altitude separations to prevent conflicts between ascending and descending aircraft. 60 corresponds to an altitude of FL60 or 6000 feet, and 70 corresponds to an altitude of FL70 or 7000 feet. At Schiphol Airport, all SIDs extend up to a maximum of FL60. An outbound aircraft may not climb higher than FL60 after departure unless cleared for a higher altitude by air traffic control. This ensures that outbound flights are always separated from inbound flights, which (without clearance) are not permitted to descend below FL70. This procedure also ensures that aircraft remain safely separated in the event of a loss of communication with one or both aircraft (LVNL, 2016). A schematic illustration of the 60/70 rule is given in Figure 3.8.

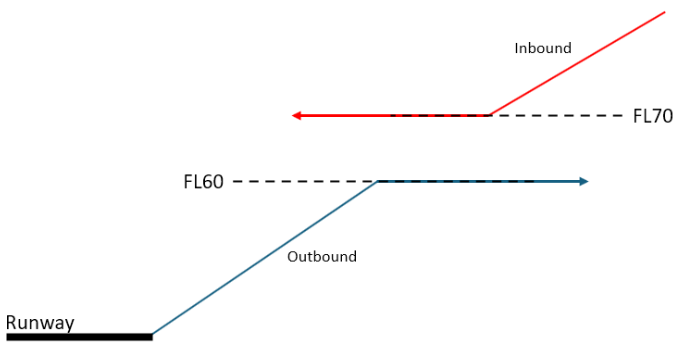

Figure 3.8: 60/70 rule vertical separation

Speed adjustments
Modifying an aircraft's speed is another effective method for conflict resolution. By instructing aircraft to increase or decrease their speed, controllers can alter the relative positions of aircraft along their flight paths. This technique helps manage longitudinal separation by adjusting the time intervals between aircraft, ensuring that safe distances are maintained.

Vectoring
Vectoring involves directing aircraft to follow different routes or waypoints to achieve lateral separation. Controllers may issue headings or route deviations to steer aircraft away from potential conflicts. This can involve minor adjustments to the planned flight path or, more significantly, re-routing around congested or restricted airspace. Vectoring is a flexible tool that allows controllers to manage aircraft movements dynamically, ensuring that separation standards are met even in complex traffic situations.

4 Research Questions

This chapter presents the research objective and questions based on previous chapters. Additionally, hypotheses are discussed.

4.1. Research objective and research questions

Research Objective

To systematically analyze and evaluate the effects of improved predictability through detailed trajectory information and flight intent across all trajectory dimensions (lateral, vertical, and speed/-time).

This objective includes examining the impact on procedure design within the operational concept of LVNL, which integrates systems, people, and procedures, specifically focusing on operations in lower airspace. The aim is to identify key improvements and potential challenges to inform more effective and efficient operational strategies in aviation.

Resulting from the research objective, the following main research question will be answered during this research:

Main-research question

How does the availability of detailed trajectory information and flight intent, which increases the predictability, in all trajectory dimensions impact the design of air traffic control procedures, within the operational concept encompassing systems, people and procedures, for improving operational efficiency and safety in lower airspace?

To be able to answer the main research question, sub-research questions have been formulated. These questions are derived from the main research question and problem statement. The following sub-research questions are formulated:

Sub-research questions

1. What are the existing air traffic control procedures for conflict detection and resolution in lower airspace?
2. How does the integration of detailed trajectory information and flight intent potentially affect the design of air traffic control procedures?
3. What specific changes do airspace/procedure designers and air traffic controllers suggest for current ATC procedures based on the availability of improved trajectory information?
4. Which operational scenarios are identified by stakeholders as critical for simulation, and why are these scenarios particularly suited for testing new procedures?
5. How do the outcomes of simulations using new ATC procedures, with detailed trajectory information, compare to existing procedures in terms of operational efficiency, safety, and environmental impact?
6. What are the quantifiable benefits and challenges of implementing new ATC procedures based on detailed trajectory information from the perspective of different aviation stakeholders?

4.2. Hypotheses

The study examines how detailed trajectory information and flight intent affects air traffic control procedures to improve operational efficiency and safety in lower airspace. To investigate this, a set of research (H_1) hypotheses have been established. These hypotheses are grouped into three categories, each corresponding to different independent variables as identified in Chapter 6.

Hypothesis on Airspace Density

- **Research Hypothesis** H_1: Increasing airspace density will negatively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly reduces the frequency of optimizations, but increases the occurrence of conflict situations.

Hypothesis on minimal separation buffers

- **Research Hypothesis** H_1: Increasing separation buffer will negatively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly reduces the frequency of optimizations and the occurrence of conflict situations.

Hypothesis on ADS-C vertical data error

- **Research Hypothesis** H_1: Increasing the vertical error in ADS-C data will positively impact operational performance metrics, including fuel burn, track miles, and flight time. Additionally, it significantly increases the frequency of optimizations and the occurrence of conflict situations.

5
Thesis framework

The thesis framework, or methodology of the overall project, will guide in answering the main- and sub-research questions. If the methodology is carefully explained, someone can perform the same research, using the same methodology and will roughly achieve the same results. In this way, you can guarantee the validity and reliability of the research (University of Southern California, 2023).

In the research, a comprehensive and structured approach to assess the impact of increased predictability in lower airspace procedure design is taken, with a focus on the capabilities of ADS-C datalinks (ATS B2 and FANS). The research will incorporate a mix of qualitative and quantitative methods. Qualitative approaches will involve conducting interviews with stakeholders to gather insights on the current state of procedure design, explore potential improvements through the use of ADS-C, and identify relevant scenarios for simulation. On the quantitative side, the study will analyze simulation outcomes based on predefined KPIs, which are explained further in Chapter 6. The methodology has been divided into five phases. A schematic format is illustrated in Figure 5.1.

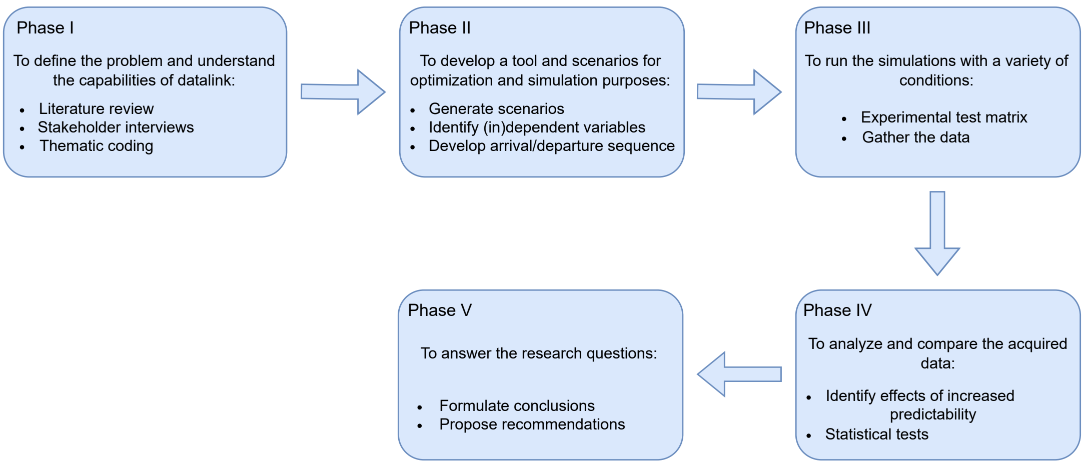

Figure 5.1: Methodology thesis

5.1. Phase I

The process begins with an extensive literature review aimed at understanding the capabilities of datalinks, specifically ATS B2 and FANS, and their role in enhancing predictability in procedure design within lower airspace. This review helps in identifying potential improvements and challenges, particularly in the use of detailed trajectory information and flight intent.

As part of the literature review, the research progresses with stakeholder interviews. A crucial step is early identification and engagement with relevant stakeholders, such as airspace/procedure designers and air traffic controllers, due to their availability and response time. There will be a mix of informal conversations and more formal interviews. For both the formal interviews and informal conversations, several pre-defined questions will be developed to extract detailed information about current procedures and potential improvements. All interviews and conversations are transcribed and included in Appendix B. Additionally, the data is analyzed using qualitative methods, such as thematic coding (Flick et al., 2004). This analysis aimed to identify key themes, especially regarding current procedural standards, potential improvements, and specific scenarios for simulations.

5.2. Phase II

The next phase consisted of several steps. Initially, it involved developing a tool that incorporates ADS-C data for optimization purposes. Additionally, this phase included creating scenarios for simulations in the ATM simulator called BlueSky, developed by TU Delft. It is an open-source air traffic management and simulation tool in Python, which is designed to provide everyone with an unrestricted way to visualize, analyze, and simulate air traffic. BlueSky can be copied, modified, cited, and shared without any limitations (Hoekstra and Ellerbroek, 2016).

The scenarios were specifically designed to simulate operations in lower airspace, based on the insights of the literature review and stakeholder interviews. However, existing ones could also be used, if appropriate for the research. Regarding the equipage rate, this study assumes a 100% equipage of ADS-C datalink for all aircraft involved in the simulations. This hypothetical setup explores the optimal potential impact and benefits of ADS-C technology on air traffic procedures in lower airspace without the variable of partial equipage rates. This assumption is critical for focusing the research on the capabilities of ADS-C datalink technology itself, rather than the current or future reality of mixed equipage levels. A more detailed description of the tool, scenarios and the experimental setup is given in Chapter 6.

Unfortunately, BlueSky does not include an Arrival Manager (AMAN) or a Departure Manager (DMAN) yet. EUROCONTROL (2010) states the objective of an AMAN as follows: "An Arrival Manager is to provide electronic assistance in the management of the flow of arriving traffic in a specific airspace, to particular points, such as runway thresholds or metering points". The same objective can apply to a DMAN, but specifically for departing aircraft. Therefore, to successfully sequence inbound and outbound aircraft to and from the runway, an AMAN and a DMAN need to be modeled within BlueSky. However, for simplicity, the initial arrival and departure sequence are pre-processed before the actual simulations. This approach saves computational power for the actual simulations.

The development of the scenarios began with defining a baseline that reflects the current state of operations in lower airspace, without the improved predictability and detailed trajectory information resulting from ADS-C. This scenario served as the control against which the experimental ones are measured. Then, with the help of the tool that incorporates ADS-C data, multiple simulation configurations were conducted, offering increased predictability through detailed trajectory information and flight intent. This facilitated an analysis of the impacts on procedural design and overall operational efficiency.

The next step was to identify (in)dependent variables for evaluation, such as operational efficiency (e.g., track miles, fuel consumption), safety margins (e.g., separation buffers, conflict situations), capacity (impact on airspace capacity), and environmental impact. This resulted in an experimental test matrix that will be further elaborated in Chapter 6.

5.3. Phase III

Furthermore, the simulation phase involved running both the baseline and other scenarios using the tool that incorporated ADS-C data under a variety of conditions. The data are then collected and prepared based on the identified variables for analysis.

5.4. Phase IV

Following the simulations, an analysis and comparison of the results from the scenarios with the tool against the baseline was conducted. This analysis seeked to identify the benefits, trade-offs, and any impacts associated with increased predictability, providing insights into the conditions under which these benefits are maximized. Finally, the findings were documented.

5.5. Phase V

The final phase of this research began with the formulation of the discussion, conclusions and recommendations. Insights from the simulation analysis were used to conclude the benefits and effects of increased predictability through detailed trajectory information and flight intent on the procedure design. Based on these conclusions, recommendations were proposed to improve procedure designs in lower airspace, alongside suggestions for future research directions.

6
Research proposal

This research proposal examines the impact of datalink technology, specifically ADS-C datalink and its IP-I/EPP trajectory, on the procedure design at Amsterdam Airport Schiphol. An extensive literature review has already been conducted, including several interviews with relevant stakeholders. The information gathered will be used to set up the research proposal. This chapter presents the research performed, the experimental setup, and the expected results.

6.1. Research performed

This study uses ADS-C datalink technology to explore potential improvements in ATC procedures. As discussed in Chapter 2, ADS-C can provide many valuable benefits to ATC, such as improved situational awareness and optimized separation buffers. The literature review and stakeholder interviews highlighted two scenarios where using ADS-C datalink could be beneficial and interesting for simulations. These scenarios included:

- Mixed approach procedures, such as RNP (EOR) and ILS approaches.
- Intersecting flight trajectories between inbound and outbound traffic.

However, due to time constraints and because, according to expert judgment, the estimated time of arrival at waypoints coming from ADS-C data in the far future of a flight is currently not accurate enough, only the intersecting flight trajectories have been chosen for simulations. Additionally, the intersecting trajectories scenario is emphasized due to its relevance to current challenges in Dutch Airspace Redesign Program (DARP), where outbound and inbound routes frequently intersect, creating potential increased workload situations for ATCOs. For this scenario, several different runs will be performed with varying variables, resulting in an experimental test matrix. These variables are further elaborated in the next section. Departures from runway 36L and 36C, as well as arrivals at 36R of Schiphol Airport, are used in this research as the runway combination. Pre-defined routes from the DARP are used, with a total run time of four hours.

The runs will be simulated and compared to a baseline in which no ADS-C data is used. LVNL's current operational design, as part of the DARP, will serve as this baseline for comparing the simulation outcomes. All simulations will consist only of departures and arrivals at Amsterdam Airport Schiphol. The primary objective of the simulations is to determine the impact of using ADS-C datalink on intersecting flight trajectories between inbound and outbound traffic. To do this, a tool must be developed to handle this specific scenario, such that trajectories can be optimized for aircraft equipped with ADS-C.

6.1.1. The tool's concept

A custom tool is developed to manage and optimize aircraft trajectories when inbound and outbound flight paths intersect. The tool dynamically identifies potential conflict situations (i.e., intersection points) between inbound aircraft landing on runway 36R and outbound aircraft departing from runways 36L and 36C. If no intersection is detected, the trajectory is fully optimized without further constraints.

In cases where an intersection is identified, the tool calculates a cylinder around the intersection point with the necessary separation distances. A 5 NM lateral and 1000 ft vertical separation buffer (or 3 NM lateral separation within the TMA) is applied to ensure safe operations. The tool then leverages ADS-C data to predict the altitude of each aircraft at a distance of 5 or 3 NM from the intersection, using linear interpolation. Since altitude, speed, and heading changes are logged, a linear relationship between these points is assumed. Therefore, this prediction method is chosen for its simplicity and effectiveness in estimating altitude changes over relatively short distances. The assumption that this approach is valid for determining the altitude is further explained in Section 6.2.6.

If the absolute altitude difference at the calculated coordinates between the aircraft exceeds the predefined separation buffer, trajectory optimization is possible. Before continuing with the optimization, the tool checks if the optimized trajectory would cause a potential conflict with another aircraft. If a conflict is found, the optimization is not performed. If no conflict is found, the tool proceeds with the optimization. This optimization involves issuing a 'direct' command to the Flight Information Region (FIR) boundary for outbound aircraft or adjusting waypoint altitude constraints for inbound aircraft, allowing them to fly unconstrained until they intercept the Instrument Landing System (ILS).

If the absolute altitude difference at the calculated coordinates is within the buffer, the tool determines which aircraft has the higher altitude near the intersection. The trajectory of the lower one is constrained to prevent a potential conflict. However, if the lower aircraft is an inbound flight and its trajectory has already been optimized, constraining this path is not ideal, as the aircraft might lack sufficient energy to descend to meet the altitude constraint. In such cases, the outbound flight is diverted from its route to avoid the potential conflict. The diversion allows the outbound aircraft more time to climb and reach a higher altitude around the intersection point.

6.2. Experimental setup

This section describes the steps in conducting the simulations, including the variables and tools used and how the ADS-C data is acquired.

6.2.1. Simulation tools

As mentioned in Chapter 5, the program that is used for this research is the open-source ATM simulator BlueSky (Hoekstra and Ellerbroek, 2016). It is chosen for its flexibility and capability to model complex air traffic scenarios realistically.

There are several ways to initiate a simulation in BlueSky. The most straightforward method is to create aircraft and their commands manually. However, for large-scale simulations, this approach may not be feasible. Another option is to use pre-defined scenario files ('.scn' files). These files can be generated using Notepad, with each line representing a command in BlueSky. A command in a scenario file consists of a timestamp, such as '00:00:00>', followed by the actual BlueSky command, for instance, 'CRE KL001 ...'. Additionally, scenario files can reference other scenario files, enabling the construction of extensive simulations in a structured manner.

6.2.2. Synthetic ADS-C data

Due to the limited availability of actual ADS-C data, this research relies on synthetic data to simulate real-world ADS-C messages. To generate this data, a baseline simulation run for each density was conducted without the optimization tool. For each change in altitude, heading, or speed, a new Trajectory Change Point (TCP) was logged. This allows the data to be used in the simulations as real-time ADS-C reports generated by the Flight Management System (FMS). A new report is generated every minute, resulting in a periodic ADS-C contract with a frequency of 1 minute. Each report updates the aircraft's current location and the predictive TCPs at one-minute intervals. However, since these reports would reflect the actual trajectory the aircraft has flown, a vertical error component was introduced as an independent variable to add a layer of realism.

The vertical error was modeled as an error rate, which introduces a bit of noise into the predicted altitudes. This error rate is determined by dividing the vertical error component, which is the independent variable, by the difference between the highest initial altitude of the simulation scenarios (FL340) and FL100, as shown in

Equation 6.1. The reason for this methodology is explained in the next section. During the generation of the ADS-C reports for a complete flight, the error rate remains constant.

$$Error\ rate = \frac{Error\ level}{(FL340 - FL100)} \tag{6.1}$$

Once the error rate is calculated, the actual error for each TCP is determined through an iterative process. For each TCP in the ADS-C report, acquired by the baseline run just described, the altitude difference between the current and predicted altitude at that point is calculated. This altitude difference is multiplied by the error rate to produce a one standard deviation (SD) error value. To introduce randomness, a normal probability density function (PDF) is applied to this one-SD error value, with the PDF centered around a mean of zero. This process adds a 'noise' factor to the predicted altitude, resulting in a predicted altitude that includes an error factor.

This method ensures that as the altitude difference between the current and predicted altitudes becomes larger, i.e., the predicted altitude is further away in the future, the probability of a larger error value from the PDF increases, leading to greater predictive errors.

6.2.3. Dependent and independent variables

This study assumes a 100% equipage rate of ADS-C datalink for all aircraft involved in the simulations. This hypothetical setup allows for the exploration of the optimal potential impacts and benefits of ADS-C technology on air traffic procedures in lower airspace without the variable of partial equipage rates. This assumption is critical for focusing the research on the capabilities of ADS-C datalink technology itself rather than the current or future reality of mixed equipage levels.

Independent variables are manipulated to observe their effect on the dependent variables. The independent variables include:

- **Airspace density:** This variable quantifies the number of arriving and departing aircraft within a specific time frame, such as an hour. Scenarios are constructed with four levels of density, minimal, low, medium, and high, designed to reflect varying traffic conditions at Schiphol Airport. The minimal category was added to assess whether there is any non-linearity in the results due to variations in airspace density.

- **Minimal separation buffer:** This represents the 'mental buffer' set by controllers to determine potential conflict situations. Additionally, it is the minimum allowable distance between aircraft that is necessary for the optimization of their trajectories. Four levels of separation buffer are used - minimal, low, medium, and high - to explore how changes in buffer size affect the optimization process and how closely aircraft can be managed while maintaining safe separation.

- **Vertical error component:** Since no clearly defined and reliable source for vertical error in ADS-C data is currently available, an estimation approach was chosen. These error values were determined based on expert judgment, suggesting that the vertical error at FL100 during descent from cruise altitude could fall within the selected range. The same logic applies to the climb. If future research provides more accurate data on ADS-C vertical errors, it will be possible to identify which of these scenarios most closely aligns with the actual error level. The study introduces four levels of vertical error, represented as one Standard Deviation (SD) value — zero, low, medium, and high — to explore how these deviations impact trajectory optimization and conflict detection.

Dependent variables are the outcomes or effects that are measured in the research to see how they change in response to manipulations of the independent variables. This research evaluates the procedure design using three categories of dependent variables: operational efficiency, safety margins, and optimized trajectories. Each category includes specific metrics that will be measured to assess the impact of the independent variables on the procedure design.

Operational efficiency

Operational efficiency is an important aspect of recent ATM, reflecting how effectively aircraft can operate within controlled airspace. It is assessed through the following metrics:

- **Track miles (distance flown):** This metric measures the total distance traveled by an aircraft from its point of origin to its destination. Reductions in track miles indicate more efficient routing and shorter flight paths.

- **Fuel consumption:** This metric measures the amount of fuel used during the flight. Lower fuel consumption is an indicator of improved operational efficiency, as it implies more efficient flight profiles and reduced environmental impact.
- **(Horizontal) flight time:** This metric refers to the total time an aircraft spends in horizontal flight or the total flight time.
- **Work done:** This metric measures the effort involved in maintaining safe separation and executing flight maneuvers. Reducing the work done suggests more streamlined and efficient air traffic management.

Safety margins
Safety margins are essential to ensure that aircraft maintain safe distances from each other and avoid potential conflict situations. This category is evaluated through the following metrics:

- **Adherence to separation minima:** This metric assesses whether aircraft maintain the required minimum separation distances from each other throughout their flight. Adherence to these minima is crucial to prevent mid-air collisions and ensure safe operations.

- **Occurrence of potential conflict situations:** This metric measures the frequency of situations where aircraft trajectories come within the separation buffer, posing a risk of conflict. A lower occurrence of potential conflict situations indicates better safety margins and more effective traffic management.

Optimized trajectories
Optimized trajectories refer to the ability of the aircraft to adjust and improve flight paths dynamically, either laterally or vertically. The following metric determines this category:

- **Number of times trajectories can be optimized/constrained:** The number of times trajectories are optimized or not optimized reflects the impact of ADS-C data on flight path adjustments. Additionally, total constraining actions are also recorded.

6.2.4. Creating the simulation files

This research utilizes fixed routes from the DARP to simulate air traffic in the Netherlands. To account for the different number of aircraft in the scenario files due to varying airspace densities, a fixed alternating pattern for route assignment was implemented. For inbound aircraft, there were four routes, and they were assigned in the following sequence: route 1, 2, 3, and 4, then repeating with route 1 again. A similar pattern was applied to runway 36C, which had six routes: routes 1 through 6, followed by a repetition of route 1. For runway 36L, which had two routes, the sequence alternated between routes 1 and 2.

A small alteration was made to the pre-defined outbound routes to simulate more realistic operations. In the original scenario files, aircraft take off immediately from the runway, but in this study, a simulated taxi time was added to account for the time it takes aircraft to reach the runway from the gate. This adjustment reflects real-world operations, where ADS-C data is available while the aircraft is taxiing. The simulated taxi time varies based on the runway: for runway 36L, the taxi time is approximately 17 minutes, while for runway 36C, it is around 12 minutes. These values were incorporated into the simulation files to better reflect actual taxiing conditions at Schiphol Airport.

Additionally, variability in aircraft type was adjusted to reflect the varying characteristics of aircraft operating at Schiphol, such as their climb, descent, and wake turbulence profiles. The distribution of aircraft types was based on real-world traffic at Schiphol, where approximately 17% of aircraft are classified as heavy types during the morning peak, dropping to 8% in the evening peak. The remaining aircraft were categorized as medium, while light aircraft were excluded from this research, as they represented a minimal percentage of the traffic in the original DARP files. Also, they are largely excluded from the normal traffic operations at Schiphol, reflecting their small presence in the real-world traffic.

Moreover, since this research used fixed routes from the DARP files, custom sequences for both arriving and departing aircraft were developed to ensure safe and realistic operations. These sequences were adjusted based on the independent variable of airspace density, forming the baseline for assessing the impact of ADS-C technology. For the arrival sequence, the flight time required for each inbound aircraft to travel from its spawning point to the runway was calculated, and aircraft were assigned timestamps with varying separation intervals depending on the applicable airspace density and travel time. Departures were sequenced according to the Wake-RECAT guidelines, with a default separation interval based on airspace density and adjustments for different aircraft categories to account for wake turbulence characteristics.

In order to introduce additional variability into the scenarios, the sequence of arriving and departing aircraft was slightly adjusted in each run. A 30-second standard deviation was applied to introduce randomness in the timing and spacing between aircraft.

6.2.5. Verification and validation

An essential part of the simulation process is validation and verification. They guarantee that the results are reliable for making informed decisions and that the tools represent the real world. For these simulations, verification steps will include code reviewing and debugging sessions, where the simulation code will be examined to ensure it is accurately implemented.

Validation processes are implemented to ensure the realism and reliability of the model and the synthetic data used in the simulations. This involves running small test scenarios to verify that the model behaves as expected under known conditions. Finally, consulting with experts in the field to review simulation scenarios and outcomes for realism and accuracy may be a proper way to validate simulations.

6.2.6. Assumptions and limitations

Because this research involves simulations, assumptions and limitations associated with the simulation of air traffic must be made. The assumptions made for this study are:

- Synthetic ADS-C data represent real-world ADS-C data.
- The trajectory of the aircraft is identical to the synthetic ADS-C data.
- Technical limitations of the ADS-C data, such as signal transmission errors, are not taken into account.

Simulations cannot perfectly represent reality. Therefore, the limitations of this research are:

- Simulations may not capture all real-world complexities, including unpredictable pilot actions and extreme weather conditions.
- Software/performance limitations of BlueSky.

6.3. Experimental test matrix

To thoroughly investigate the impact of various factors on ATC procedures in lower airspace, this research utilizes a comprehensive experimental test matrix. The matrix integrates multiple independent variables at different levels, ensuring a systematic and controlled approach to examining their effects on operational efficiency and safety margins.

6.3.1. Research variables

The study considers the following independent variables, each set at different levels to capture a wide range of scenarios:

Airspace Density: Reflects typical operational conditions, varying from low to high traffic volumes. This value represents the density per runway, distinguishing between arriving and departing aircraft. Therefore, a density of 36 departures per hour and 34 arrivals per hour means 36 aircraft depart from each used runway at Schiphol, while simultaneously, 34 aircraft arrive at Schiphol.

- **Arrivals**
  - Minimal (17 aircraft per hour)
  - Low (30 aircraft per hour)
  - Medium (34 aircraft per hour)
  - High (38 aircraft per hour)
- **Departures**
  - Minimal (17 aircraft per hour)
  - Low (32 aircraft per hour)
  - Medium (36 aircraft per hour)
  - High (40 aircraft per hour)

Allowed Separation buffer: Set at three levels to understand its influence on the 'mental buffers' set by controllers to determine potential conflict situations.

- Minimal (1000 ft)
- Low (2000 ft)
- Medium (3000 ft)
- High (4000 ft)

Vertical error component: Represents the accuracy of the ADS-C trajectory data used in the simulations.

- Zero error (0 ft)
- Low error (100 ft)
- Medium error (200 ft)
- High error (500 ft)

6.3.2. Matrix Configuration

The experimental test matrix uses a full factorial design, which includes all possible combinations of the levels of each independent variable. Each configuration is replicated only once since the BlueSky simulator is a deterministic program. To illustrate the structure of the matrix, the first six rows and the last is shown in Table 6.1. The complete matrix is given in Appendix A.

Table 6.1: Experimental test matrix

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
1	Minimal	Minimal	Zero error
2	Minimal	Minimal	Low Error
3	Minimal	Minimal	Medium Error
4	Minimal	Minimal	High Error
5	Minimal	Low	Zero error
6	Minimal	Low	Low Error
...	...	...	...
64	High	High	High Error

6.4. Performance assessment

As explained in Section 6.2.3, the procedure design is evaluated using three categories of dependent variables: operational efficiency, safety margins, and optimized trajectories, each with their specific metrics. To measure these dependent variables, a series of simulations will be performed under various conditions set by the independent variables. Data will be collected for each run and metrics will be computed as follows.

6.4.1. Operational efficiency

Table 6.2: Metrics for operational efficiency

Metric	Description	Source
Track Miles (Distance Flown)	Extracted from the BlueSky built-in array `bs.traf.distflown`, which logs the total distance flown by each aircraft from origin to destination.	`bs.traf.distflown`
Location of ToD	Identified by analyzing the vertical speed data from the BlueSky built-in array `bs.traf.vs` to determine the point where the descent begins.	`bs.traf.vs`
Fuel Consumption	Calculated using the built-in array `bs.perf.fuelflow`. Each recorded fuel flow value (in kg/s) is multiplied by the time step (`dt`, which is 1 second) and summed to get the total fuel consumption in kilograms for each flight. Although this variable might not provide the most precise determination of fuel flow, it serves as a relative value when compared to a baseline. This allows for the measurement of increases or decreases in fuel consumption. Consequently, conclusions regarding improved efficiency can be drawn from these comparisons.	`bs.perf.fuelflow`
(Horizontal) flight time	The duration of an aircraft's flight from its initial position to the runway is calculated. Additionally, the amount of horizontal flight time is logged, defined as periods where the vertical speed is zero.	`bs.traf.vs`
Work done	Calculated using the built-in array `bs.perf.work`, this determines the total amount of work done by the aircraft throughout the flight.	`bs.perf.work`

6.4.2. Safety margins

Table 6.3: Metrics for safety margins

Metric	Description	Source
Adherence to Separation Minima	Evaluated using the built-in Airborne Separation Assurance System (ASAS) in BlueSky, which detects potential conflicts based on look-ahead time and set separation minima.	ASAS in BlueSky
Occurrence of Potential Conflict Situations	Counted based on how often aircraft trajectories fall within or exceed the separation buffer when there is an intersection.	Simulation logging

6.4.3. Optimized trajectories

Table 6.4: Metrics for Optimized Trajectories

Metric	Description	Source
Number of Times Trajectories Can Be Optimized/Constrained	Tracked by counting the instances where trajectory optimization occurs or any constraining actions and noting when it does not happen due to defined reasons in the model.	Simulation logging

6.5. Expected results

This study is designed to yield comprehensive and quantifiable insights into the impact of ADS-C datalink technology on procedure design in lower airspace, particularly in scenarios involving intersecting flight trajectories. The expected results are formulated to demonstrate the effectiveness of ADS-C in enhancing operational efficiency.

The simulations are anticipated to demonstrate a noticeable reduction in track miles flown by aircraft, which in turn would lead to lower fuel consumption and decreased CO2 emissions. However, according to DSNA et al. (2023), less track miles does not necessarily mean less emissions. It is also dependent on the altitude and performance of the aircraft. It is expected that the introduction of ADS-C will enable optimal altitude profiles, thus, together with the reduction of track miles, enhancing the overall efficiency of the airspace.

Airbus et al. (2020) states: "Flights with early descents and a longer descent phase with intermediate level offs result in significantly higher fuel consumption and CO2 emissions.". Therefore, it is expected that due to the optimization of trajectories, the ToD will be further in the future, resulting in a higher altitude and later descents. Consequently, if the ToD is further away, fuel consumption is expected to be lower.

With the improved situational awareness provided by ADS-C, the simulations should show a significant decrease in potential conflict situations. This will be quantified by measuring the instances where separation minima are breached compared to the baseline scenario.

A

Experimental test matrix

Table A.1: Complete experimental test matrix

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
1	Minimal	Minimal	Zero error
2	Minimal	Minimal	Low Error
3	Minimal	Minimal	Medium Error
4	Minimal	Minimal	High Error
5	Minimal	Low	Zero error
6	Minimal	Low	Low Error
7	Minimal	Low	Medium Error
8	Minimal	Low	High Error
9	Minimal	Medium	Zero error
10	Minimal	Medium	Low Error
11	Minimal	Medium	Medium Error
12	Minimal	Medium	High Error
13	Minimal	High	Zero error
14	Minimal	High	Low Error
15	Minimal	High	Medium Error
16	Minimal	High	High Error
17	Low	Minimal	Zero error
18	Low	Minimal	Low Error
19	Low	Minimal	Medium Error
20	Low	Minimal	High Error
21	Low	Low	Zero error
22	Low	Low	Low Error

Continued on next page

Table A.1 – continued from previous page

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
23	Low	Low	Medium Error
24	Low	Low	High Error
25	Low	Medium	Zero error
26	Low	Medium	Low Error
27	Low	Medium	Medium Error
28	Low	Medium	High Error
29	Low	High	Zero error
30	Low	High	Low Error
31	Low	High	Medium Error
32	Low	High	High Error
33	Medium	Minimal	Zero error
34	Medium	Minimal	Low Error
35	Medium	Minimal	Medium Error
36	Medium	Minimal	High Error
37	Medium	Low	Zero error
38	Medium	Low	Low Error
39	Medium	Low	Medium Error
40	Medium	Low	High Error
41	Medium	Medium	Zero error
42	Medium	Medium	Low Error
43	Medium	Medium	Medium Error
44	Medium	Medium	High Error
45	Medium	High	Zero error
46	Medium	High	Low Error
47	Medium	High	Medium Error
48	Medium	High	High Error
49	High	Minimal	Zero error
50	High	Minimal	Low Error
51	High	Minimal	Medium Error
52	High	Minimal	High Error
53	High	Low	Zero error
54	High	Low	Low Error
55	High	Low	Medium Error
56	High	Low	High Error

Continued on next page

Table A.1 – continued from previous page

Test ID	Airspace Density	Separation buffer	Synthetic Data Error
57	High	Medium	Zero error
58	High	Medium	Low Error
59	High	Medium	Medium Error
60	High	Medium	High Error
61	High	High	Zero error
62	High	High	Low Error
63	High	High	Medium Error
64	High	High	High Error

B

Transcribed interviews

B.1. Conversation with Danny Verdoorn and Jonah Bekkers

One significant observation was that, due to the relatively small size of the Dutch Flight Information Region (FIR), the ToD for aircraft often lies within other FIRs in neighbouring countries. Consequently, LVNL has limited influence over this aspect, impacting the planning process for air traffic controllers. They expressed a desire to receive this data earlier to facilitate more efficient planning (Verdoorn D. Bekkers J., Personal communication, February 6, 2024).

Additionally, the speed schedule coming from the EPP was identified as an interesting use case for air traffic management. This approach underscores the significance of adjusting aircraft speeds to match specific airline cost indices, a strategy aimed at optimizing fuel consumption and operational costs. For instance, if one aircraft adjusts its speed to align with its airline's cost index for economic efficiency, and another aircraft selects a different speed to achieve its own cost optimization, this variance in speeds can naturally prioritize aircraft sequencing. Such prioritization allows for more efficient management of aircraft flow within congested airspace, as aircraft with differing speeds will arrive at the Initial Approach Fix (IAF) at separate times, minimizing interference with each other's paths (Verdoorn D. Bekkers J., Personal communication, February 6, 2024).

Looking towards the future, the integration of datalink technology was discussed as a beneficial enhancement for air traffic control operations at LVNL. However, it was noted that the adoption of datalink would necessitate an additional screen due to the current Amsterdam Advanced Air traffic control system (AAA) screen being fully occupied. This adaptation is seen as essential to accommodate the extra features provided by datalink technology. It was also mentioned that if an aircraft lacks datalink capabilities, operations would continue as presently conducted. In contrast, aircraft equipped with ADS-C datalink would benefit from additional features, potentially operational efficiency in airspace management (Verdoorn D. Bekkers J., Personal communication, February 6, 2024).

B.2. Conversation with Stefan van der Loos

In a recent conversation with Stefan van der Loos, an air traffic controller, several insights into ATC operations and technology were shared. Stefan discussed various aspects of ATM, including the implementation and benefits of datalink and the application of ADS-C for enhancing flight safety and efficiency (van der Loos S., Personal communication, February 7, 2024).

Datalink technology, despite its infrequent issues with incorrectly inserted Standard Terminal Arrival Routes (STARs) and Standard Instrument Departures (SIDs), is seen as a potential tool for improving aviation safety, even if the improvements are marginal; safety enhancements are always beneficial. However, Stefan views conflict detection via ADS-C, using only the intent data, as less interesting, given that the primary concern for ATCOs is maintaining sufficient separation between aircraft to ensure safety. If the ADS-C trajectory data shows that two aircraft are crossing each other's flight paths, at a minimal vertical or lateral distance, then this data needs to be 100% accurate to use for conflict detection. The ATCO prefers to be on the safe side and will likely intervene to increase their separation. The ATCO has the primary responsibility for maintaining a safe distance (van der Loos S., Personal communication, February 7, 2024).

As previous controllers also confirmed, the interest in ToD is limited for Dutch ATCOs, as it typically occurs outside the Netherlands, therefore the influence on this point is limited. However, ADS-C is valued for its ability to provide detailed trajectories of aircraft, including the EPP, which aids in anticipating and managing aircraft movements more effectively. Stefan mentioned that it is very interesting to know at which time and altitude the aircraft arrives at a certain waypoint. With this information, the ATCO can make informed decisions on its future actions. The reliability of data is paramount, with Stefan highlighting the importance of accuracy, as exemplified by errors in down linked aircraft barometer readings from Airbus, which can significantly impact operational decisions (van der Loos S., Personal communication, February 7, 2024).

Simulation scenarios that are of interest include monitoring outbound speeds and managing inbound congestion, a process referred to as "bunging", which involves adjusting aircraft speeds or routes to ensure efficient spacing for landing sequences. Monitoring times and altitudes at EPP waypoints against radar data presents an interesting opportunity for validating and enhancing the accuracy of this data (van der Loos S., Personal communication, February 7, 2024).

Regarding possible KPIs to use for measuring during simulations, defining capacity in ATC operations is complex, influenced by numerous factors. Stefan plans to provide a document that further explores this topic, which could offer valuable insights into the challenges of capacity measurement. Furthermore, environmental impact, from Stefan's perspective, directly correlates with efficiency in flying, where more efficient flight paths lead to reduced emissions (van der Loos S., Personal communication, February 7, 2024).

Finally, the utility of ADS-C is not diminished by some aircraft lacking ATS B2 capabilities. The key is understanding which information is available and how it can be used for operational benefits for those aircraft that are equipped with ADS-C (van der Loos S., Personal communication, February 7, 2024).

B.3. Interview with Tristan Meerburg

Can you describe the current procedures in lower airspace? What are the steps you follow to arrive at new procedures?

I don't know exactly what kind of information you're looking for, but it's a big picture. Difficult to focus so broadly. In the Netherlands, especially at Schiphol ACC and APP, we have a certain preference for traffic operations that we have become accustomed to over the years and in which we are quite good at. Our infrastructure, represented by the black lines on the maps, we have published and serves to support this. Although aircraft will regularly follow the mapped routes, it is often the case that traffic controllers are forced to divert traffic from these routes due to traffic conditions. This is because we are often faced with an abundance of traffic and in an unstructured manner. Our job is then to create an ordered flow from this, which is then "sequenced" and transferred to Approach. Approach then has the space to further 'sequence' this flow and fine tune it for the final approach so that all aircraft can land separately.

The routes and approaches we establish are primarily for planning purposes. However, if we look at the actual flight routes, they will usually not match the planned routes, except in situations when it is very quiet. Then traffic can be directed according to these routes. But even then not, because our routes usually have corners and kinks. In situations where there is no traffic, it is not necessary to follow them exactly, so the traffic situation makes it possible to take a shorter route. So, when the traffic situation allows us to fly shorter, we choose the shorter route. However, when the traffic situation requires sequencing aircraft for safe handling, we may have to take a longer route.

Response to his answer (Thijs)

So, in this context, certain procedures may apply to how this should be carried out, but this is primarily based on assessing a variety of external circumstances. Whenever possible, more direct routing, or in other words, following different routes than originally determined, is preferred. This is necessary because the standard route is not always feasible, mainly because of limited capacity.

Response from Tristan
With us, traffic doesn't actually fly around predetermined routes. We manage the air within which we have to separate, sequence and time traffic. Those are the goals we need to achieve, and we have a certain piece of air available to achieve those goals. While talking, I realize that my knowledge of ADS-C may not be extensive, but of ADS-B I know a little bit. I am aware that there is information in aircraft that can be downlinked. If Ferdinand informs me about this, I can see how valuable that could be. I'm not completely sure, but within ADS-B, for example, there is something like pilot selected level, from which we can detect errors. Also, I see that the barometric pressure setting, the QNH, is downlinked.

In certain situations, especially when we perform RNP approaches, it is crucial that the QNH is set correctly. Fortunately, we now have tools and alerts that the system provides us with, thanks to information that is downlinked. Looking at what Ferdinand sometimes shows me about the availability of information in ADS-C, such as the intent, the programmed route, and data on "time-over" times and altitude, I think that, for planning purposes, this information can be put to good use.

We manage the crane located at the Schiphol TMA, where inbound scheduling is located, known as ASAP. Although the exact operation is beyond my expertise, I know that ASAP is currently fed with information we collect ourselves. We observe traffic, note the expected time over a given point (stack) and begin scheduling times. This process results in a customized schedule and produces different delta T's, where our goal is to reduce this delta T to zero so that traffic can be requested for a unit in a structured manner. In this process, I see significant opportunities for leveraging more valuable information from the aircraft itself to optimize our scheduling.

Can you give examples of how data link can be used in procedure design in the future?
Yes, I'm more focused on the present because I think the procedures and rules are the way they are. When we receive accurate information, we can make more accurate schedules based on that. These schedules are then flown better, which makes them more predictable. I believe that in time, as we build confidence that aircraft will do exactly what we expect, the kinks we put into routes - to protect ourselves and add or save extra miles - may partially disappear. Once these kinks are out, the overall line gets shorter. This means that when you plan a route, it is shorter, requiring less kerosene. Carrying less kerosene means less weight to fly with, so in total we use less kerosene, resulting in fewer emissions.

Response by Thijs to his answer
So, actually, it might be just the opposite world. Now the procedures and lines are as they are, but through ADS-C Data Link, you could fly more directly with information directly from the aircraft. Then you could possibly modify official procedures. This could be a preliminary approach, allowing us to shift the lines to a more direct route, thanks to the information received directly from the aircraft.

Response from Tristan
As for other applications, I must confess that my view of what information can all be downlinked is still quite immature. Perhaps when we talk again, we can discuss this in more detail. I want to give you a clearer picture, a sense of where this information can be valuable. I know that intent, like the programmed route, is an important element that is downlinked and that we are very interested in. This is especially relevant with a departing aircraft on the runway. In a number of operations, especially parallel operations, it is crucial that the aircraft turns right. If it were to turn left, it could end up in the path of another aircraft. We have to be absolutely certain that once the plane takes off, it actually makes the right turn. We have several safety barriers built in to ensure this. Still, sometimes mistakes happen. One way to be even more certain that the correct route is programmed is to downlink the route and see the first waypoint, or otherwise visually confirm the route. As long as we are sure that the aircraft is not going left, we can assume that it will go right correctly.

Response from Thijs
The Flight Management System (FMS) plays a crucial role because the data link information comes directly from the FMS. You show that the route has been programmed correctly in the FMS and that we can proceed on that basis. This indeed confirms that everything is set and programmed correctly, allowing us to proceed with confidence. This principle also applies to Standard Terminal Arrival Routes (STARs), where the proce-

dure may be slightly less likely to cause problems. However, with Standard Instrument Departures (SIDs), the risk of deviations is perhaps greater, making it all the more important to verify through the data link that the correct procedures have been programmed. This process is also immediately critical, perhaps more critical than in other operations.

Response from Tristan
However, it does happen, because in my opinion our sectors 1 and 2 have a more complex arrival structure, dealing with two or three arrivals that we always use and two other arrivals that we almost never use. Nevertheless, all these arrivals are programmed with the same heaviness in the FMS. So it is possible that you might accidentally select the wrong one, which could result in turning in the wrong direction.

Would Flexible Use of Airspace (FUA) be a good application of datalink?
Last year at a conference I spoke to an air traffic controller from MUAC who talked about ADS-C, which excited me. This controller demonstrated how an airspace would be activated and how an aircraft could indicate that if it flew directly, it would be at a specific point at a certain time. And if it took a detour, at what time it would arrive at another point. Thanks to the ADS-C information, which indicated that the plane could reach that point in time, it was possible to give the plane a direct route through that area before it became active. This kind of information is something we didn't have until now.

Response from Thijs
No that's right, and with that intent they can also see at certain waypoints whether the plane will be at a specific point at that time. Of course, you're always dealing with an estimate, but that remains an estimate. However, based on that information, it is possible to send the aircraft through military airspace when it will only become active in a few minutes (flying around 15 to 20 min in Dutch airspace). Thus, you can still take advantage of all kinds of benefits and make efficient use of the airspace before it is closed to civilian traffic.

Response from Tristan
We deal with level restrictions and crossing conditions on our routes for various reasons. This may be to keep the airspace near the airport clear or to enter appropriate airspace at our neighboring countries, where we have crossing conditions on the routes. When we get altitude information directly from the aircraft, about the expected altitude at a given point, we can determine early whether the level restriction or crossing condition will be met. This allows us to coordinate more timely with neighboring countries or to find a solution. So we can better coordinate with our neighbors to confirm if everything is OK, or we have more time to look for an alternative solution.

Could Continuous Descent Operations (CDO) also be a valuable application?
In the context of an airspace revision, one of the main objectives is to make operations at Schiphol more sustainable. This is directly translated into the need to enable more Continuous Descent Operations (CDOs). This requires fixed approach routes, as the pilot needs to know the number of track miles to the runway to accurately determine his top of descent. From that point, it should be possible to fly a CDO through to the runway, achieving an efficient and fuel-efficient descent.

We developed a design where the first version included long fixed approaches from the edge of the TMA to the runway. However, the current version of our design includes short fixed approaches starting from 6000 ft, where there is still room for vectors up to the approach point. I find it challenging in this design, specifically for the CDO and thus for the fixed approaches over which a CDO would soon be flown, to determine the minimum length required to perform a good CDO. This is because the effectiveness of a CDO is highly dependent on several factors such as aircraft type, weight, and wind conditions. There are numerous variables that determine the ideal top of descent.

I saw this complexity reflected in the simulations with approach. I had designed a path with an expected vertical profile, but that remains an expectation, perhaps a conservative one. When we ran this with approach, I could not pinpoint exactly where aircraft would actually leave 6,000 or 10,000 feet. I think it would be valuable to discuss this with an approach controller. So it is valuable to be able to see where aircraft actually leave their altitude on the laid out path.

Response from Thijs
Theoretically, this could be possible by using the aircraft's intent to see where it is by waypoint, according to the Flight Management System (FMS). This could provide a glimpse into the future, especially if there are other constraints. Of course, this will require adjustments, but you can actually see by waypoint where the aircraft is currently and what the time of that is. However, it is important to recognize that this time indication may not always be very accurate, as it can be affected by various factors.

Response from Tristan
I think the time factor is less important at Approach because the traffic flow is already regulated. The Approach controller's job then is to manage the traffic and make sure it stays neatly sequenced and separated, either on the Final Approach track or at the approach point for the fixed approach.

Explaining what I did during my internship (Thijs)
Altitude is of particular interest at this stage. During my internship, in which I processed data from MUAC and integrated it into BlueSky, at iLabs, I visualized to make the intent visible on the screen. This allowed you to see the data down to orbit, including different elevations.

Response from Tristan
It would be really great if we could do this on iLabs. The platform is popular with ACC controllers and Approach controllers, who are eager to use it. I have noticed a lot of thinking about how we can leverage the ADS-C information. This is reminiscent of how MUAC began, simply by showing their informational element, without directly attaching a procedure or obligation to it. When the information is available, it starts to come alive and people start thinking about how it can be used. Imagine if we were to do an approach simulation on iLabs. We could make a button that would make the top-of-descent or trajectory available. If you have two seconds to spare, you could turn it on and see if it helps you. Or you could help us create insights about how you would use this information.

Response from Thijs
Yes, that is indeed a good one. I can already show the data link information, which I've already done, and that's already nice. It's really interesting, as Ferdinand also rightly pointed out. He showed this to some air traffic controllers, and they were enthusiastic.

Response from Tristan
For example, the trajectory with the expected altitude, which I hadn't mentioned before, is also definitely an issue, also in the airspace review. Given the geography of the Netherlands, the work area, and the location of the runways, there are sometimes unavoidably difficult intersections of inbound and outbound routes. These types of intersections pose significant challenges and increase the workload for controllers who must anticipate or proactively act to keep them clear of each other. It is crucial to properly clear these situations because such a conflict can significantly increase the workload. But if you can see the intent of the route with the expected altitude at a given point, and it appears that everything is in order, this can significantly reduce the workload to determine a conflict.

Response from Thijs
This principle is discussed a lot online, especially in the context of conflict detection, where it can be a valuable application. You can see the intent of trajectory and have certain points where aircraft are at specific altitudes. Of course, you still always have to be careful and responsibility remains. However, it can provide a certain peace of mind, or rather, confirmation that everything is going according to plan, while you still have to remain alert and possibly take action.

Not many aircraft are equipped with datalink yet, what do you think the impact of this would be if not all flights have this technology available to them?
I am trying to make the link to the "equipage rate. The evolution of ILS approaches to more RNP (Required Navigation Performance) or GPS approaches required by EASA regulations also presents challenges. Political and policy decisions encourage their adoption, but if not all aircraft can perform these approaches, there will be a mix of traffic flows. This mix can be difficult for air traffic control.

We cannot simply replace our ILS approaches with just RNP approaches because there will always be a portion of traffic that cannot perform them. This would lead to a mix of traffic operations, which is always undesirable. Therefore, such a change cannot be forced into the operation. ADS-C information, which is complementary, is relevant here. Having this information is always an asset that allows you to make better decisions. And if that information is not there, you always have enough information to make a good decision. ADS-C data for heavies would be especially interesting.

Response from Thijs
Heavies already have an older version of datalink, FANS ADS-C, developed around 1990. Although it was never mandated by EASA or other agencies and thus not widely used, it does contain intent information, albeit less accurate with only up to 10 waypoints in the future. The EPP (Extended Projected Profile) in ATS B2 can show up to 128 waypoints, which is much more detailed and can provide essential information for navigation.

Response from Tristan
Regarding challenges in airspace management, especially for "heavies" who especially cannot climb over such a conflict. This is especially difficult in a mix of traffic where some aircraft are capable of RNP approaches and others are not, leading to complex traffic handling. Suppose the traffic handling requires that you have an information element from ADS-C, then everyone must be able to do it, or the critical mass must be able to do it.

In the development of procedures, it is crucial that almost everyone must be able to follow them, ideally more than 99% of the traffic, because procedures must be designed to work for the concept we came up with, but must also be robust against disruptions. This means that the system must function even if someone cannot follow the required procedure. As illustrated with the 3D profiles, we aim that in 95% of cases, traffic will naturally remain free of each other. However, there should always be enough flexibility to solve the 5% of cases where this fails.

This highlights why some attractive and short-looking routing concepts are not feasible; they look efficient for the majority, but do not address the anomalous cases. When transitioning to new systems, such as RNP, it is essential that everyone can implement them before alternatives such as ILS can be removed. It is crucial to always have an alternative that allows similar traffic handling.

For example, there is enthusiasm about RNP Authorization Required (AR) approaches, which allow sharper routes than the general criteria allow. Although these are primarily intended for obstacle and mountain navigation, some see potential for use in flat areas, such as the approach to Amsterdam. However, this would create a mix of traffic flows, which is undesirable. A possible solution could be to have aircraft equipped for AR approaches perform them while other traffic is given a visual approach, supported by GPS, to keep traffic flow uniform. This would be an innovative way to take advantage of existing technologies without disrupting traffic flow. However, it would not be feasible to line up all traffic shortly before the op with AR, and longer must on lines with ILS. Then you get a very weird mix of wrong which makes it very difficult.

What do you think would be critical or specific scenarios that I can include in my simulations.
We have now mostly discussed very generally about some applications of ADS-C that we could use. But I don't yet have a complete sense of how ADS-C could be used under FL245. I would like to know exactly what comes out of ADS-C data, and thereby be able to get a better sense of what might be possible. Although it's too early to identify concrete improvements, conversations you've had with Johan, Danny, and Stefan encourage which information elements of ADS-C are most valuable.

By thinking about how this data can change operations, I can develop scenarios both with and without ADS-C and examine how traffic operations differ. This process of evaluation, though still in its early stages, promises to offer insights into how we can make air traffic control more efficient and effective using ADS-C, even if I don't currently have a complete picture of exactly how this would work.

A concrete example I have in mind concerns the intersecting inbound and outbound paths that are critical to us. Without ADS-C information, we would be tempted to give instructions to level off, leading to more noise and fuel consumption as aircraft are in the air longer. With ADS-C information, we might not need to give such instructions, or could give a different instruction with a different effect on noise, fuel consumption, and track miles. This is a concrete application based on what I just described.

Response from Thijs
Stefan also mentioned a similar point, related to sequencing at the outbound of air traffic. I wonder if this would have the same effect. ADS-C information would possibly allow you to climb faster to a certain altitude, if you see, for example, that the airspace is clear up to that altitude. Or is this fixed in certain procedures? This could lead to a different type of sequencing or reaching a desired altitude faster, depending on available airspace. This raises the question of whether procedures could be modified as a result, so that aircraft, equipped with the right information, can climb to their destination more efficiently.

Response from Tristan
Then don't you need ADS-C data from many aircraft?

Response from Thijs
Yes that's right, that is a drawback to that, but that may be an assumption of my simulations. That a lot of chests have that. Or with certain percentages.

Response from Tristan
Controllers ensure that aircraft always climb to an altitude that is definitely clear. As an aircraft approaches this altitude, it is cleared to the next free altitude, in line with the developing traffic situation. In time, we might dare to rely on aircraft intent, although this still seems a long way off.

Response from Thijs
I could explore this to a certain extent by specifically selecting flights that are known to carry aircraft already equipped with ADS-C. It does not make much sense to speculate on flights for which we do not have coverage. In this way, I can simulate scenarios where there is ADS-C data available and see how this affects traffic flow and the decision-making process.

Response from Tristan
This consideration leads me to the idea that, if all aircraft are equipped with ADS-C, this could have a significant impact on how we handle information and thereby improve our understanding of how traffic conditions develop over time.

Response from Thijs
With access to intent or other information from all aircraft, this could lead to one of my ultimate conclusions: reducing separation and optimizing procedures, although safety always comes first. This could also contribute to a reduction in emissions, since aircraft could follow their optimal trajectory in an ideal world where everyone can optimize their path.

Response from Tristan
The more predictable the flow of traffic becomes, the easier it is to provide a path with as few corrections as possible for the pilot. This allows them to optimize their route, ultimately leading to more efficient flights and potentially less fuel consumption and emissions.

Response from Thijs
Yes, that's exactly what I'm trying to do: simulate the potential impact and applications of ADS-C information in air traffic control. Although I do not yet know exactly how to shape this, I am already exploring and experimenting to find out. It is indeed challenging to find a good application at this time, especially since the use of ADS-C is not yet mandatory and thus not widely integrated into operational procedures.

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