Evaluating the impact of prediction accuracy on Continuous Descent Operations: The added value of Trajectory Predictor performance through Air-Ground Datalink

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by

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Preface

This report, presented to you, marks the conclusion of my extensive and enduring journey toward obtaining a master's degree in Aerospace Engineering at Delft University of Technology.

I would like to express my immense gratitude to my parents, whose unwavering support, love, encouragement, and sacrifice have been the cornerstone of my academic journey, leading me to where I am today. To my sister, my brother-in-law, my dear niece, and their wonderful family, I extend my gratitude for their continuous love, support, and understanding throughout the ups and downs of my master's program and thesis work. Their positive influence not only provided a supportive environment for my research but also contributed to a sense of warmth and connection throughout my journey here.

I would like to thank Ferdinand, Jacco, Joost and Evert for their supervision, guidance, support and encouragement without which this research would have been impossible to complete. I would also like to thank Susan for going the extra mile and providing me guidance during my entire masters journey at the university.

I extend my sincere appreciation to my fellow KDC-CoE and iLabs colleagues for their insights and help during my research work. I also thank them for the numerous laughs and cherish the coffee break conversations, which have added a pleasant and vibrant dimension to this research journey.

I would like to express my appreciation to my friends for their unwavering love, support, and encouragement. They provided a comforting escape during challenging times and served as a source of motivation, propelling me back into my pursuits.

I am pleased to successfully conclude my academic journey and am enthusiastic about applying my acquired skills and knowledge in a professional capacity within the industry.

Mithun Raghunandan
Rotterdam, February 2024

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Nomenclature

Abbreviations

Abbreviation	Definition
ACC	Area Control Center
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
AGDL	Air Ground Data Link
AMAN	Arrival Manager
AMS	Amsterdam Airport Schiphol
ANOVA	Analysis of Variance
ANSP	Air Navigation Service Provider
AO	Aircraft Operators
APP	Schiphol Approach Control Center
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATN-B2	Aeronautical Telecommunication Network: Baseline 2
ATS	Air Traffic Service
CDA	Continuous Descent Approach
CDO	Continuous Descent Operation
EAT	Expected Arrival Time
EPP	Extended Profile Projection
FMS	Flight Management System
FPL	Flight Plan
GUI	Graphic User Interface
IAF	Initial Approach Fix
iLabs	InnovationLabs
KDC	Knowledge and Development Center
KIAS	Knots - Indicated Airspeed
LVNL	Luchtverkeersleiding Nederland/ Air Traffic Control The Netherlands
MUAC	Maastricht Upper Area Control
SESAR	Single European Sky ATM Research
TMA	Terminal Manoeuvre Area
TOD	Top of Descent
TP	Trajectory Prediction
VDL-2	Very High Frequency Data Link-2
VEMMIS	Veiligheid, Efficiency en Milieu - managementinformatiesysteem
VHF	Very High Frequency

Part I

Thesis Paper

Evaluating the impact of prediction accuracy on Continuous Descent Operations: The added value of Trajectory Predictor performance through Air-Ground Datalink

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Abstract

This thesis investigates the role of time prediction accuracy in optimizing Continuous Descent Operations (CDO) within the aviation sector, with a specific focus on assessing the additional benefits brought forth by the integration of Air-Ground Datalink technologies. Continuous Descent Operations, characterized by uninterrupted and efficient descent profiles, hold promise for reducing fuel consumption, emissions, noise, and overall operational costs. However, the extent to which accurate time predictions contribute to the success of CDO remains a critical yet understudied aspect.

Keywords: *Continuous Descent Operations, Trajectory Prediction, Extended Projected Profile (EPP), ADS-C, ATN-B2*

1 Introduction

Airports such as Amsterdam Schiphol Airport (AMS) are constantly in a pursuit of exploring avenues to augment their capacity to handle more aircraft movements. As one of the busiest hubs in mainland Europe, AMS plays a pivotal role in both the economy of the Netherlands and the European Union. However, despite its status, the airport faces operational constraints. Regulatory measures, driven by environmental targets, and discontent among local residents have curtailed further expansion. Consequently, optimizing traffic flow at AMS takes precedence as the facility already operates at maximum capacity.

The future concept for arrivals at AMS, as for many airports, is to progressively implement Continuous Descent Operations (CDO). The specific approach that aircraft follow during a CDO is referred to as a Continuous Descent Approach (CDA). For this, it is already known that a high degree of predictability of the arrival trajectories is needed. Research has shown that the quality of the Trajectory Prediction (TP) can be improved by leveraging information from the aircraft [1]. With new Air Ground Datalink (AGDL) technology emerging, specifically Automatic Dependent Surveillance - Contract (ADS-C) from Baseline 2 datalink, these possibilities are becoming within reach. However, it is unclear to what extent the integration of this AGDL provided information will enhance TP performance. Moreover, the sensitivity of the managed arrival process to the predictability of the trajectories, both in the prediction as well as the execution phase of the arrival is unclear. Having a better insight in this dependency enables the further design of the technical concept by providing target performance levels. In turn, it also provides direction and input to the business case for equipage by airlines for trajectory sharing as well as ground system trajectory prediction performance. To establish a useful measurement for value added by improved predictability of the success rate, that is, the percentage of CDA that can be executed without Air Traffic Controller's (ATC) intervention, is envisioned.

1.1 Research Objective

The objective of this research is to establish a relationship between prediction accuracy and the successful execution of a continuous descent approach. For this research, ***"During its descent from the Top of Descent (TOD) until the Initial approach fix (IAF) the descent is said to be a successful CDA if there are no level segments in the aircraft's descent profile and the aircraft is not laterally vectored"***. In other terms, it is said to be an unsuccessful CDA if the aircraft is in a conflict

path with another aircraft during its descent because an intervention by air traffic controller is warranted when an aircraft is in conflict. This resolution would be in terms of either lateral vectoring or instructing it to stop its descent and maintain its altitude. For this study, the aircraft is said to be in a level segment if its descent rate is less than 300 ft/min for more than 20 seconds. This threshold for defining a level segment is derived from similar research, such as [2], that studied vertical flight trajectory efficiency at AMS.
This study is performed to answer the following research question:
"How does varying the time prediction accuracy in the arrival process of aircraft at AMS in high density situation affect the ability for executing continuous descent approach procedures successfully?"

1.2 Research Hypothesis

With the research question defined, it can be hypothesised that by increasing the prediction accuracy of the trajectory the number of CDAs flown increases because by having a more accurate aircraft trajectory the number of aircraft in conflict paths would decrease which would mean there is less intervention from the air traffic controller. As the prediction error increases the number of conflicts would increase thus the rate with which a CDA can be executed would decrease. It can also be expected that as the altitude decreases, the number of conflicts would increase because at lower altitudes the speeds are lower and the traffic is converging towards the runway which would mean increase in aircraft traffic density thus more chances of conflicts.

2 Background

It is widely acknowledged that numerous airports in Europe are currently operating at nearly full capacity, primarily attributed to a consistent rise in air traffic density over the years [3]. Despite a brief decline in air travel during the pandemic, there has been a noteworthy rebound. Consequently, Air Navigation Service Providers (ANSPs) are under heightened pressure to uphold designated time slots for planned flights while ensuring the required high level of safety. As mentioned earlier, airports face the challenge of striking a balance between regulatory constraints and revenue enhancement. AMS is currently facing societal and governmental pressure to reduce the number of aircraft movements. This call arises from concerns related to air quality targets in the region and the noise experienced by residents along flight paths. Modern systems on aircraft such as ADS-B, constantly pass on information to the ground. This system is called Automatic Dependent Surveillance where crucial information such as the aircraft's position, velocity and flight plan information from the flight management system of the aircraft can be broadcast to the ground. This information might help us increase the accuracy of aircraft trajectory prediction. The European Organisation for the Safety of Air Navigation (EUROCONTROL) and Airbus [4] are studying the effects of increasing trajectory prediction with their research on Trajectory Based Operations (TBO). EUROCONTROL is conducting research on the impact of integrating data from ADS-C into Air Traffic Management (ATM). The research, as indicated by [5], suggests various benefits, such as efficient aircraft trajectories and traffic management.
This research specifically focuses on the Extended Projected Profile (EPP) that is defined by the Aeronautical Telecommunication Network: Baseline 2 (ATN-B2) and transmitted by ADS-C from aircraft to ground systems. This EPP is a message that contains information about the reference trajectory calculated by the aircraft's flight management computer. EUROCONTROL has mandated ATN-B2 standard in 2017 [6].

2.1 Automatic Dependent Surveillance (ADS)

Automatic Dependent Surveillance (ADS) is a type of surveillance in which aircraft automatically transmits information obtained from its onboard navigation and position fixing systems via a datalink. The information that is transmitted depends on the type of ADS system equipped on the aircraft. There are two different types of ADS systems: ADS-B and ADS-C. The difference between the two is as shown in Table 1.

2.1.1 Automatic Dependent Surveillance - Broadcast (ADS-B) ADS-B is a type of surveillance where the aircraft and other vehicles equipped with the system automatically broadcast their identity, horizontal and vertical position, emergency status without any external stimulus. The broadcasting source has no knowledge of who receives its broadcast data. ADS-B is used to establish spatial awareness between aircraft and is used to achieve various benefits such as improved performance, improved safety, increased capacity. ADS-B uses Mode-S transponders to broadcast data.

2.1.2 Automatic Dependent Surveillance - Contract (ADS-C) Automatic Dependent Surveillance - Contract (ADS-C) is a type of air traffic surveillance systems that has the capability to give air navigation

Parameters	ADS-B	ADS-C
Transmission	Automatic and is transmitted to all ADSB receivers.	Automatic but is only transmitted to receivers that has a contract with the broadcaster.
Data Transmitted	Horizontal position Barometric altitude Aircraft Identification Emergency Status Special Position Indicator	Basic Group Flight Identification Group Earth Refernce Group Air reference Group Airframe Indication Group Meteorological Group Predicted Route Group Fixed projected intent Group Intermediate Projected intent Group
Mandated to equip on commercial aircraft	Yes	No

Table 1: *Differences between ADS-B and ADS-C*

service providers access to aircraft information. The information that it transmits typically consists of its position, altitude, speed, meteorological data and importantly for this thesis, its navigational intent usually obtained from flight management computers only to one or more specific air navigation service providers. ADS-C uses Very High Frequency (VHF) Datalink, known as VDL-2 radios that support controller pilot datalink transfer, that is, sending data between aircraft and ground stations. The data transmitted from ADS-C is shown in Table 1. ADS-C provides much more information as compared to ADS-B and is categorized into groups and the broadcasting source knows exactly to whom it is sharing its data. The data transmitted as a result from a request from ANSP depends on the contract held by the ground system. The different types of contracts of ADS-C are:

- **Periodic Contract** This type of ADS-C contract enables the ANSP to define the time interval at which the aircraft sends the report to the ground and it also lets the ANSP to define the optional ADS-C groups that are to be reported.
- **Demand Contract** A demand contract enables the ANSP to request a single ADS-C periodic report.
- **Event Contract** An event contract allows the ANSP to request ADS-C report when a specific event occurs. The ANSP can only establish one event contract with an aircraft at any one time. However, the event contract can contain multiple optional events such as waypoint change, level range change, lateral deviation, vertical rate change.

The pilot through the aircraft needs to request to log on to the ANSP's server. This then enables the ANSP to downlink important aircraft intent from its flight management computer like the EPP to the ANSP's server which can then be used to make decisions regarding its flight path. ADS-C was originally used for oceanic remote operations where the aircraft trajectory information was downlinked to ground. But with the newly introduced ATN Baseline 2, the target is to use it to all operations. ATN-B2 allows the downlink of EPP which consists of an updated flight management system's route prediction which is much more detailed than the current ADS-C reports. For instance it includes the predicted aircraft weight and the predicted horizontal and vertical speeds on upto 128 future waypoints in its flight route [7]. Maastrict Upper Area Control (MUAC) has recently started operational use of ATN ADS-C [5] for its trajectory based operations.

2.2 Current operational procedures for arrivals into AMS

This research is focused on arrivals into AMS, thus understanding the current operational procedure becomes important. Air traffic flying into AMS is monitored and controlled predominantly by the Dutch ANSP, Luchtverkeersleiding Nederland (LVNL). In general, inbound Schiphol traffic flows from the Area of Responsibility (AoR) of an adjacent centre via an Amsterdam Area Control Center (ACC)-controlled area (sector) to the Schiphol Approach (APP)- controlled Schiphol Terminal Maneuvering Area (TMA). The ACC Air Traffic Controller (ATC) transfers inbound traffic to the Schiphol Approach (APP) at the initial approach fix located near the boundary between the ACC sector and the Schiphol TMA as shown in Figure 1.
In the Figure 1 the traffic flows from left to right, but the planning of the inbound flow is carried out from right to left. That is, the inbound flow is planned by

Figure 1: *Traffic flow for arrivals into AMS*

assigning a flight to a particular runway. A landing sequence is then built based on the landing interval per runway. An arrival manager (AMAN) schedules the aircraft sequence based on the current runway operating conditions. Once this landing interval is established the Expected Arrival Time (EAT) is calculated. This is the target delivery time for en-route (ACC) ATCs to deliver the aircraft at IAF. The ATCs must deliver the aircraft at IAF at EAT within an allowable margin of 120 seconds. The initial approach fix is a point in the aircraft's arrival route where the aircraft has descended enough to be able to begin its approach to the runway. The descent from the IAF until the runway threshold can be a continuous descent or the aircraft can be vectored depending on the traffic density in the Terminal Manoeuvre Area (TMA) and the Tower Control zone (CTR).

2.3 Type of Approach

Descent is the segment of flight where the aircraft begins to descend from its cruise level such that it can arrive at its destination. Airports with low traffic density generally instruct aircraft to descend from its top of descent in a continuous glide down towards the runway, as shown by the green flight profile in Figure 2. Another kind of approach that is generally used is a stepped approach, where the aircraft descends from TOD towards the runway in 'stepped' segments and is as shown by the red flight profile in Figure 2. That is, the aircraft's descent profile has level segments in them or 'steps'. The findings from studies like [8] and [9] indicate that employing a CDA during landing not only reduces fuel consumption but can also serve as an effective noise abatement procedure, as supported by research in [10]. The research conducted in [11], specifically focused on high-density operations at AMS, aligns with broader research on CDA, emphasizing the potential for decreased fuel burn.

In AMS a continuous descent approach is used when the traffic density is low, that is, usually during night time operations. When the traffic density is high, a stepped approach is used. This can be attributed to the fact that in the calculation of the descent path by the flight computers, the ATC is left out of the loop as critical values such as mass of the aircraft is not shared and also different aircraft performance varies. Thus, reducing the control for ATC in case of

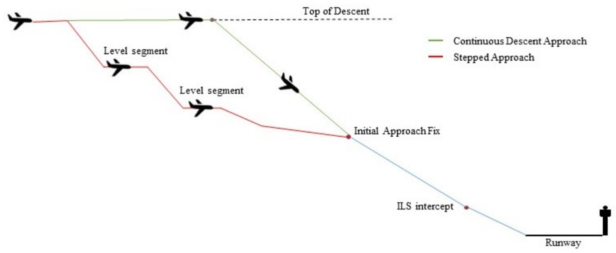

Figure 2: *Different approaches for descent.*

conflicts. No studies have looked into the effect that the prediction of aircraft arrival at IAF has on the execution of a continuous descent approach. Ideally an idle continuous descent approach is desired as this is more beneficial in terms of fuel burnt and emission as compared to off-idle CDA [12]. However, controlling aircraft's descent speed becomes difficult in idle CDA, for instance, if an aircraft needs to loose speed, it would have to do so by employing speed-brakes which is wastage of energy and could be a cause of discomfort for passengers. From the safety point of view, off-idle CDA is preferred over idle CDA because, in case the aircraft needs to abort its descent for any unforeseeable reason such as conflict, the engine spool-up time for off-idle CDA is less as compared to aircraft performing an idle CDA. Thus for this research, an off-idle continuous descent approach is selected.

3 Simulation Design and Experimental Setup

The objective of this research is to investigate how prediction accuracy influences the successful execution of CDAs. To achieve this, a comparative analysis is conducted, focusing on variations in the number of CDAs executed across different prediction error ranges. The entire simulation process is illustrated in the flow diagram presented in Figure 3. Multiple simulation runs are performed, enabling a comprehensive comparison and evaluation. Statistical tool, such as the F-test, is employed to assess the simulation's statistical significance. The subsequent section provides a detailed description of the simulations and outlines the simulation setup for a comprehensive understanding of the study's methodology.

3.1 Data

For this research work the quality and the quantity of data plays a pivotal role. The study is conducted at the Knowledge and Development Centre (KDC) - Schiphol, where access to precise historical data is facilitated through collaborative efforts with partners

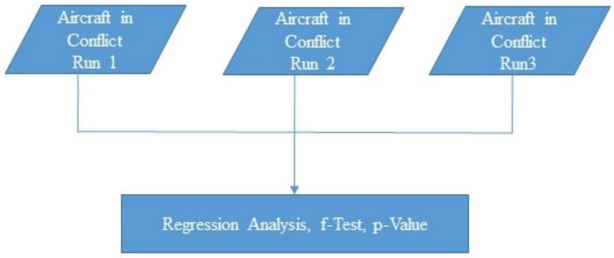

Figure 3: *Flow diagram of multiple simulation runs.*

such as LVNL and EUROCONTROL. Veiligheid, Efficiency en Milieu - managementinformatiesysteem (VEMMIS), a LVNL database, encompasses various components, including radar data, weather data, track data, and routes. For this research, VEMMIS is used to obtain the spawn position and condition of historical flights that flew into Schiphol over the span of one day in August of 2019 which amounts to 758 flights. A pre-covid data is considered since traffic was still unaffected then.

3.2 Simulation Design

To simulate and examine the influence of prediction accuracy on CDA, it is essential to begin by clearly defining the variables involved. The independent variables of this research can thus be defined as prediction error (seconds) and traffic density (number of aircraft per given day). According to the research objective, the dependent variable would then be success rate of executing CDA. To measure the success rate, an intermediate dependent variable, the number of aircraft in conflict, is introduced. As the prediction error increases, it is likely that the number of conflicts will also increase. This is because the introduction of more randomness and errors in the trajectory prediction raises the likelihood of aircraft encountering conflicting paths. An increase in traffic density is expected to contribute to a higher occurrence of conflicts as the increased presence of multiple aircraft in flight simultaneously raises the probability of encountering conflicting paths.

To establish the relation between prediction error and number of conflicts a simulation needs to be performed. Thus to run these simulations, an air traffic management simulation environment is needed.

3.2.1 Simulation Software This entire research is designed such that an air traffic management software is needed to perform the analytical calculations and to observe conflicts. For this work, BlueSky [13] is used as an ATM simulator tool. BlueSky is an open source, python based, user friendly, air traffic management simulator which has high fidelity. Numerous researches have satisfactorily used BlueSky for simulations and verification. A Scenario file is created, which is a text file that is used to feed instructions (scenarios) to run the simulation. Since BlueSky is an open-source simulator, there are multiple variations of it developed for specific use. The version of BlueSky used for this research is obtained from InnovationLabs (iLabs) [14]. This version is chosen because iLabs, a collaborative effort between LVNL and Delft University of Technology, is actively developing a customized closed source BlueSky using proprietary data specifically designed for AMS. To accurately replicate aircraft performance in the simulation, the ATM simulator relies on an aircraft performance model. In this study, the chosen model is sourced from iLabs and is tailored for assessing aircraft performance within traffic bound for AMS. Constructed with proprietary data from iLabs and its collaborators, this model is intricately designed to closely mirror the actual traffic performance into AMS, making it better suited for this research.

After choosing the simulation tool and the performance model, the simulation of aircraft flying into AMS must be configured. As mentioned earlier, this research employs VEMMIS to acquire historical aircraft data. It precisely captures the aircraft's entry into Dutch airspace, known as the spawn time, along with three-dimensional spatial information, including the aircraft's altitude, longitude and latitude. The aircraft must then be instructed to fly a specific route into its approach to one of the runways. The runway combination used for this research is arrivals into Runway 18R and Runway 18C. This instruction is fed into the software by creating a scenario file.

3.2.2 Creating the arrival route This study employs fixed arrival routes for runways 18R and 18C, representing the most frequently utilized combination at AMS. Operationally, Dutch airspace is laterally divided into five sectors, as illustrated in Figure 5. Sector 1 is situated in the northeast, Sector 2 in the east, Sector 3 in the south, Sector 4 in the southwest, and Sector 5 in the northwest of Dutch airspace. The scenario file is configured to guide aircraft arrivals from Sector 1 and Sector 2 to Runway 18C, while arrivals from Sector 3, 4, and 5 are directed to Runway 18R. To ensure realistic descents closely resembling operational procedures, speed and altitude restrictions are enforced over predefined waypoints in the arrival route. The dutch airspace is vertically divided into airspaces as shown in Figure 6. The area of focus for this research, as previously defined, is from the TOD until the IAF. The airspace that is of focus is the Control Area (CTA) in this case, the Amsterdam Control Center (ACC). The scenario file is created such that the aircraft flies from its spawn position towards the IAF as shown in Figure 5 and then fly the approach into its designated runway. The orange points

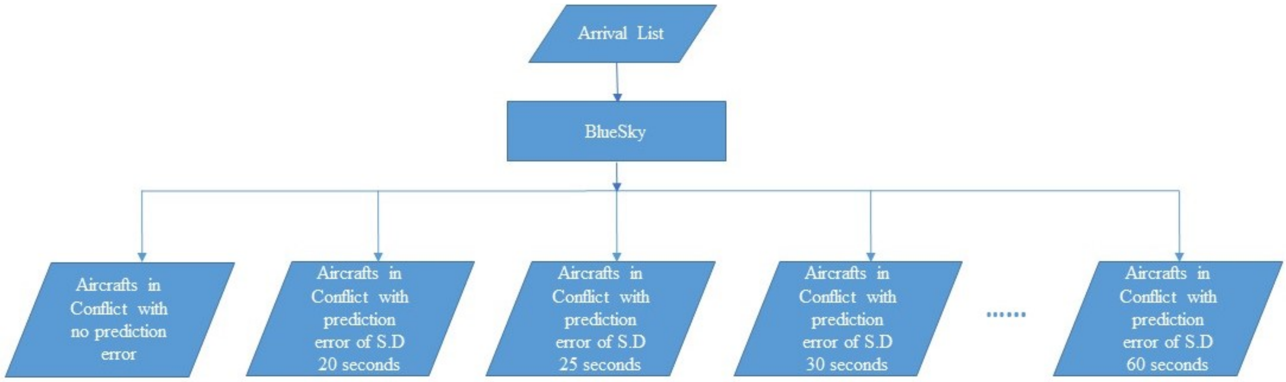

Figure 4: *Flow diagram of performing one experimental run.*

in the figure indicate the aircraft spawn position.

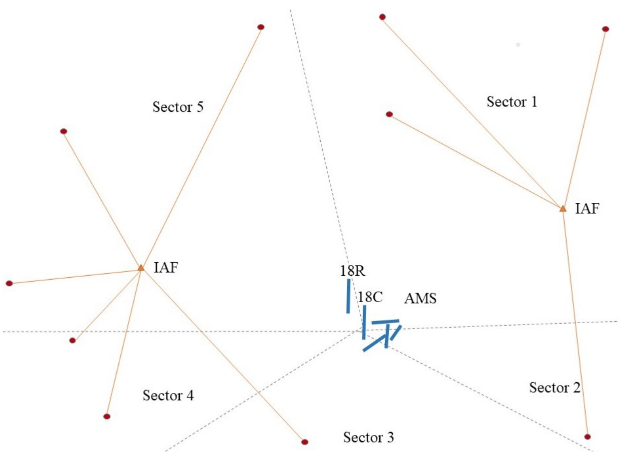

Figure 5: *The fixed arrival route and the sectors of the Dutch airsppace.*

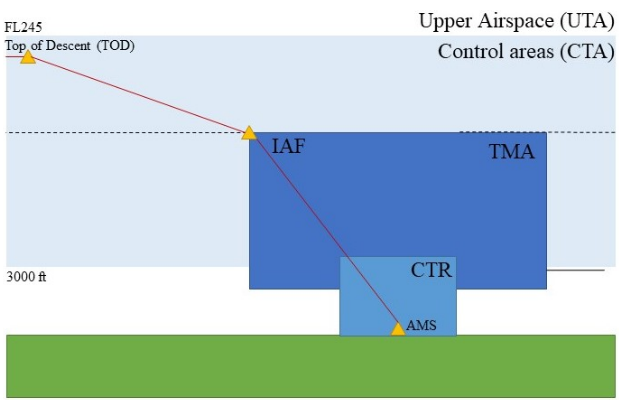

Figure 6: *Dutch Airspace*

As explained previously and as shown in Figure 3 multiple simulation run is to be performed to establish the relationship between the number of aircraft in conflict and the prediction error. The setup of a single simulation run is as shown in Figure 4. A sequence of aircraft arrivals is subjected to various range of prediction error and the number of conflicts is recorded for further analysis. A sequenced arrival is thus needed before the simulation can be performed.

3.2.3 Obtaining an Arrival sequence An arrival sequence of aircraft is needed such that they can be subjected to the uncertainties of the prediction error. This is done by a tool called as an AMAN. It creates a sequence of aircraft separated by a given time interval. For this thesis the inter arrival time, that is, the time between aircraft arrivals at the runway threshold, is set to be 90 seconds. To make it simpler, let us use an example to explain how this arrival sequence is created. Let us say a flight 'KLM001' enters the dutch airspace at 00:00:00 and then takes 20 minutes to arrive at the runway threshold at 00:20:00. Another flight, 'KLM002' enters the dutch airspace at 00:03:00 and takes 17 minutes to fly to the runway threshold, which means it would also arrive at the threshold at 00:20:00, which is the same arrival time as 'KLM001'. AMAN would then give KLM002 a landing slot of 00:21:30 which is 90 seconds after the arrival of 'KLM001'. This is done for all aircraft arrivals and a sequence is obtained. It is to be noted that in order for 'KLM002' to arrive at the runway threshold, it needs to be delayed by 90 seconds from its initial arrival time of 00:20:00. Now in current high density operations, this delay would be added to the aircraft in terms of speed manipulation or by radar vectoring. But for this research, any radar vectoring would deem the CDA unsuccessful. Another solution in the simulation to enforce this delay could be that the aircraft could be spawned later such that it arrives at the runway at its allotted slot. But in practice this would mean asking the adjacent air traffic center to delay the aircraft's entry into the Dutch airspace, which is not desired. Thus for this simulation, the delay is enforced by changing its Target Descent Speed (KIAS). To achieve this target descent speed for each aircraft, a database is created which has the information of each flight of 758 flights that arrive into AMS which contains the time the flight takes to fly from its spawn position to the runway

threshold for different target descent speeds. In the database, the target descent speed is varied from 200*kts* to 270*kts* to obtain the flying time of the aircraft. In this example, let us say 'KLM002' takes 20 minutes to fly with an initial target descent speed of 270*kts*. In our example, it is desired that 'KLM002' flies an additional 90 seconds to meet its assigned landing time. The AMAN looks into the database for 'KLM002' and selects a target descent speed that has a flying time of 21 minutes and 30 seconds, let us say for this case, it corresponds to a target descent speed of 250*kts*. Thus for this instance, AMAN would create a sequence of 'KLM001' arriving at 00:20:00 with its original target descent speed and then 'KLM002' arriving at 00:21:30 with a modified target descent speed of 250*kts*. The AMAN does this to all aircraft flying into the runway and creates an aircraft arrival sequence and provides a target descent speed for the aircraft to achieve this sequence.
This research uses descent speed control to achieve the correct EAT adherence thus the accuracy of prediction influences the success with which the timing of aircraft arriving at EAT can be effected instead.
There are two methods by which aircraft's EAT adherence can be influenced: Air traffic controllers managing the speed targets or, alternatively, the aircraft calculating and controlling the speed target. In the context of this research, the decision has been made to have ATC manage the speed targets. This aligns with operational practices observed at LVNL, where a similar approach is taken due to the necessity for predictability in speed patterns, particularly in the context of high-density operations.

Upon setting up the simulation software, selecting the performance model, obtaining the aircraft spawn data and an arrival sequence, the simulation as illustrated in Figure 4 can be performed to record conflict counts under varying levels of prediction error. Initially, a baseline number of aircraft conflicts is established, acting as a benchmark for comparison with conflict counts observed under different prediction error cases. Analyzing this aircraft conflict count further gives us the rate at which CDAs can be successfully implemented.

3.2.4 Establishing a Baseline As briefly explained before, a baseline is obtained which record the number of aircraft in conflict without any noise added to the arrival sequence, or, with a prediction error of 0 *seconds*. While one might intuitively expect a 100% success rate in executing CDA in this baseline, the reality is more complex. The irregularity in arrivals at AMS, characterized by multiple "Arrival Peaks" with heightened air traffic density, challenges this expectation. During peak periods, air traffic controllers might employ strategies like vectoring or placing aircraft in holding patterns to ensure separation requirements. However, in adherence to the CDA definition, simulations in this research refrain from such vectoring practices and instead utilize speed control to delay aircraft arrivals. Nevertheless, there is a limit to how much an aircraft can be slowed down. Thus, the baseline simulation, despite having no prediction error, may still experience conflicts due to the non-uniformity of arrivals throughout the day.
The flow diagram of establishing this baseline is as shown in Figure 7. The data, which consists of historic aircraft data obtained from VEMMIS is first fed into AMAN and a sequence of arrival is obtained as explained in the previous section and this acts as the input. It is fed into the simulation software and the output is processed to obtain the number of aircraft in conflicts. This baseline serves as the benchmark against which the outputs of other simulations, conducted with varying prediction errors, are compared.

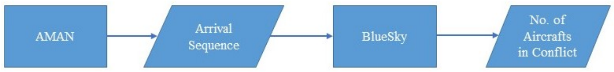

Figure 7: *Obtaining Baseline conflict values.*

After establishing the baseline, it is imperative to conduct simulations with diverse prediction errors to facilitate an analysis of the number of aircraft conflicts. This analysis involves comparing the outcomes of these simulations with the baseline values. The variables are the same as the simulation run to obtain the baseline, that is, number of conflicts is recorded for varying prediction error.

3.2.5 Simulations with varied Prediction Error To investigate the impact of prediction error on CDA, the simulation proceeds by introducing noise to aircraft arrivals once the baseline is established. Specifically, the spawn time of aircraft is modified, incorporating noise in terms of standard deviations. The number of conflicts is then systematically recorded for various prediction errors. In this research, the range of prediction errors spans from 20 seconds to 60 seconds 1-sigma, with an increment of 5 seconds. This chosen range allows for correlation with similar studies, such as the research conducted by SESAR in PJ38 [15]. The workflow for recording conflicts at different standard deviations is illustrated in Figure 8.

A full simulation run, as depicted in Figure 3, is considered complete once both the baseline simulation and simulations with varying prediction errors have been executed. In the context of this research, three complete simulation runs are conducted. This facilitates the execution of subsequent statistical analyses, allowing for the application of the F-test and en-

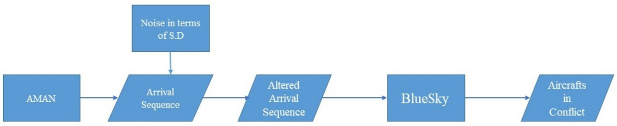

Figure 8: *Changing the prediction error and finding the number of conflicts.*

abling a more thorough evaluation of the relationship between the dependent and independent variables.

3.3 Statistical Analysis

Upon the completion of all three simulation runs, additional analysis is essential to comprehend the output and establish the relationship between the variables. The primary objective of this research is to assess the influence of prediction error on the successful execution of CDAs. This evaluation involves examining the impact of prediction error on the success rate of flown CDAs. The success rate is determined by assessing the number of aircraft in conflicts, as instances of conflicts indicate unsuccessful execution of a CDA. While these values are derived from the simulation runs as previously explained, it is crucial to consider the statistical significance of any variations in output of these simulations. A regression analysis is performed in this research to determine the impact of prediction error on the number of conflicts.

3.3.1 Regression Analysis Once the simulation is done, the output is processed using a statistical tool to understand the result. As previously stated, this research uses regression analysis to understand the result of the simulations. Regression analysis is chosen since the relationship between the prediction error and the number of conflicts needs to be established. A non linear regression analysis is chosen instead of a linear regression analysis as non linear linear regression analysis is used to model complex behaviour between dependent and independent variables. It uses a non-linear function to fit complex patterns in data. The general form of a nonlinear regression model involves a nonlinear function that relates input variables to the response variable, with parameters estimated through optimization techniques. The equation of a nonlinear regression model is given by:

$$y = f(x, \beta) + \varepsilon \tag{1}$$

where y is the dependent variable, x is the independent variable, β represents the vector of regression coefficients, $f(x, \beta)$ is the non-linear regression function, and ε is the error term.

This research involves a comparative analysis of simulations conducted using air traffic management software. An F-test is then performed to further understand the output. The primary objective of running the F-Test or Analysis of Variance (ANOVA) is to assess the statistical significance of the variability in the number of conflicts observed across three simulation runs. This assessment aims to discern whether the observed variations are random or if there is a systematic effect of the independent variable (prediction error) on the number of conflicts. In essence, the goal is to examine if the variability in the number of conflicts obtained from running the simulations three times is significantly influenced by prediction error.

3.3.2 F-Test / Analysis of Variance (ANOVA) The F-test stands as a robust statistical method extensively applied in the domain of Analysis of Variance (ANOVA). Its primary function is to assess the statistical significance of observed variations among multiple groups, determining whether these differences are meaningful or might have occurred randomly. This test is particularly valuable when comparing means across diverse datasets. In the ANOVA framework, two crucial hypotheses are central to the F-test:

- **Null Hypothesis** (H_o)**:** The null hypothesis posits that the means of all compared groups are equal. This implies that any observed variations in the data are attributable to random sampling variability rather than true group differences.

- **Alternative Hypothesis** (H_1)**:** In contrast, the alternative hypothesis suggests that at least one group mean is significantly different from the others. A rejection of the null hypothesis implies the presence of meaningful differences among the group means.

For this research, the hypotheses are framed as:

- **Null Hypothesis** (H_o)**:** *"The variation in the number of conflicts across the three simulation runs is solely due to random chance, and there is no systematic effect of prediction error on the number of conflicts."*

- **Alternative Hypothesis** (H_1)**:** *" The variation in the number of conflicts across the three simulation runs is not solely due to random chance, and there is a systematic effect of prediction error on the number of conflicts."*

The F-test generates an F-statistic, a numerical summary that quantifies the ratio of the variance between groups to the variance within groups. A higher F-statistic indicates a greater likelihood of significant group differences. The associated p-value is a critical metric obtained from the F-test. Researchers compare the p-value to a predetermined significance

level (commonly 0.05) to make decisions about the null hypothesis. A low p-value (typically below the chosen significance level) leads to the rejection of the null hypothesis, signifying that observed differences among group means are statistically significant.
To summarize, the F-test serves as a robust tool to determine whether observed variations in the data are indicative of true group differences or if they can be attributed to random chance. The interpretation of the F-test is essential for drawing meaningful conclusions about the factors contributing to variability among groups. In the context of this study, the application of the F-test is aimed at assessing whether the variance in the number of conflicts obtained from the three different simulations with varying levels of prediction error is statistically significant. The null hypothesis posits that the observed variance in conflict occurrences across different levels of prediction error is solely due to random chance, indicating no systematic effect of prediction error. The predetermined significance level of the p-value for this research is set to be 0.05.

3.3.3 Rolling Window Analysis To comprehend the trends of aircraft arrivals throughout the day and their impacts more effectively, an analysis known as a Rolling Window Analysis can be conducted. The Rolling Window Analysis, also referred to as a moving window or rolling window regression, is a statistical method employed to evaluate the stability or trends of a data series over time. In this analysis, a window of fixed size moves through the dataset, and statistical computations are performed for each window. After each calculation, the window advances by a specified increment, and the process is repeated until the entire dataset is covered. In this research, the analysis is carried out to comprehend the number of aircraft arrivals within a 20-minute time window throughout the entire day. The aim is to understand the trending patterns of aircraft arrivals over the course of the day. The actual operational saturation limit at AMS is 10 aircraft per window of 20 minutes. Exceeding this limit indicates that the runway is operating beyond its full capacity, while a value below 10 suggests that the runway has not reached its capacity yet. Looking at the results of analysis could help explain the behaviour of arrivals into the runway.

4 Results

This section presents the outcomes of the simulation and analysis performed as explained in the previous sections. The primary aim of this research is to assess how prediction accuracy influences the successful implementation of a CDA. The independent variable in this evaluation is the prediction accuracy, while the dependent variable is the success rate of executing a CDA. To measure this success rate, an intermediate dependent variable is considered—the number of aircraft in conflict. This choice is based on the assumption that any aircraft in conflict would prompt intervention from the air traffic controller, either through employing level segments or radar vectoring. Both interventions are deemed unsuccessful CDAs according to the definition established in this research.

4.1 Number of Aircraft in Conflict

The number of aircraft in conflict for varying range of prediction error for all three simulations for arrivals into runway 18R is as shown in Table 2. It can be observed that the number of aircraft in conflict does not vary much across the three simulation runs. The result of f-test which was performed to understand the statistical significance of variation of these conflict values is presented further in detail in the upcoming section. The table depicts that the number of aircraft in conflict increases with increasing prediction error. In simulation run 1, for a prediction error of 0 seconds 182 aircraft were in conflict which increases to 222 aircraft in conflict as a result of a prediction error of 20 seconds. That is an increase of 40 counts of aircraft in conflict for simulation run 1 whereas the increase in conflict counts for simulation run 2 and run 3 are 45 and 42 respectively. The data from the table can be visualised as shown in Figure 11. The Success rate of executing a CDA across the three simulations for varying prediction error is tabulated in Table 3. The success rate of implementing a CDA in simulation run 1 decreases from 59.73 % for no prediction error to 50.88% for a prediction error of 20 seconds and the decrease is of a similar magnitude for run 2 and run 3. A graph that shows the success rate for the three simulation runs are as shown in Figure 9.

The number of conflicts for arrivals into runway 18C is as shown in Table 4. The simulation shows that, for arrivals on runway 18C, the number of aircraft in conflict is insensitive to the prediction error. Increase in prediction error does not seem to show any effect on the rate with which a CDA can be executed. The rate of successful CDA hovers around 62%. The rolling window analysis for arrivals into runway 18C is as shown in Figure 13 and for arrivals on 18R is as shown in Figure 14.

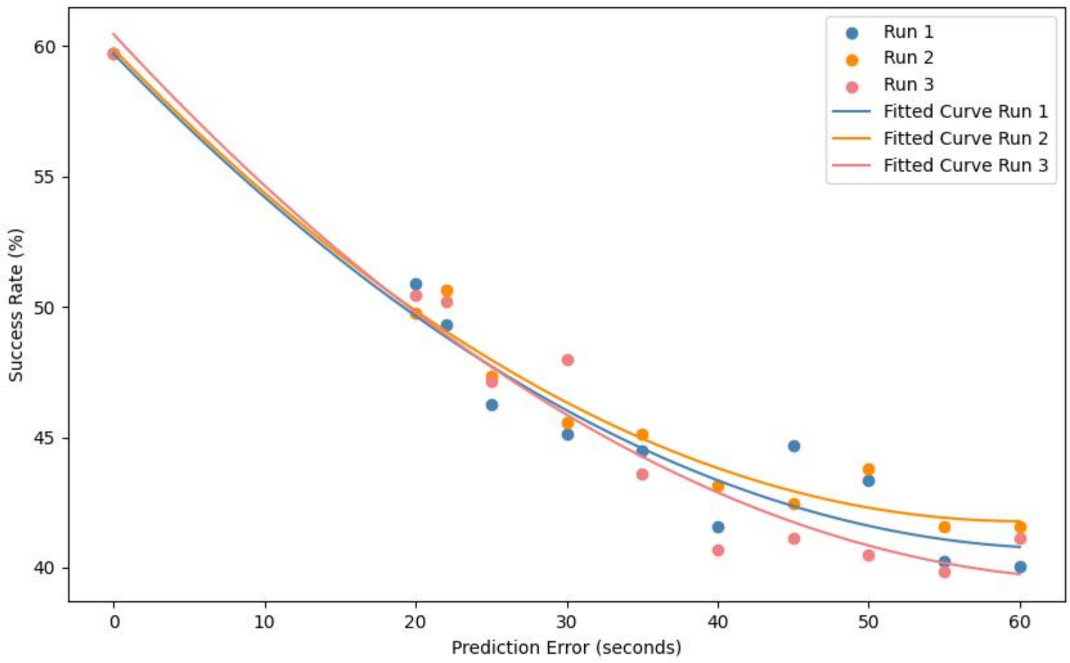

Figure 9: *CDA success rate for varying prediction error of arrivals into runway 18R.*

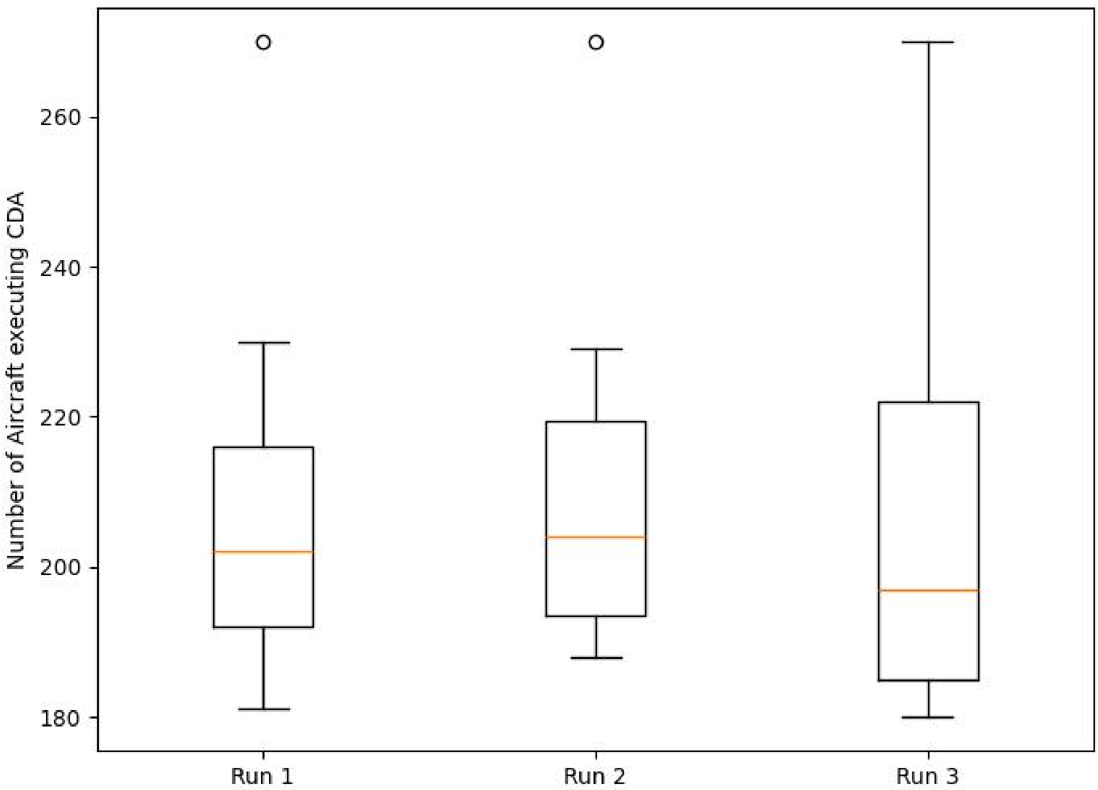

Figure 10: *Box Plot of number of aircraft successfully executing a CDA for varying prediction error of arrivals into runway 18R.*

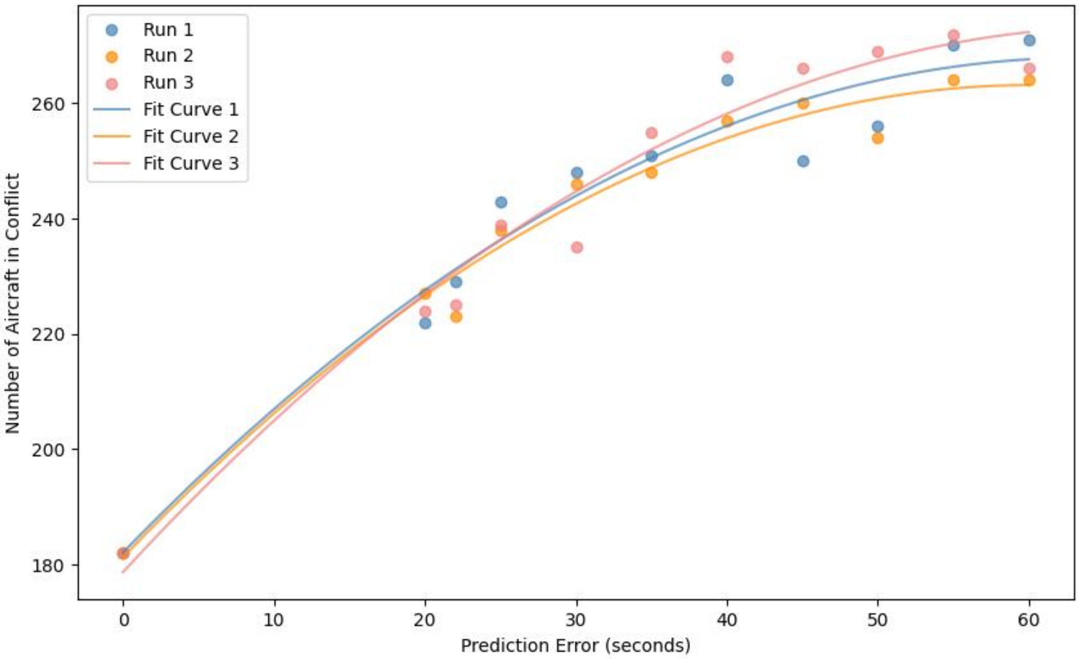

Figure 11: *Number of aircraft in conflict for the three simulation runs.*

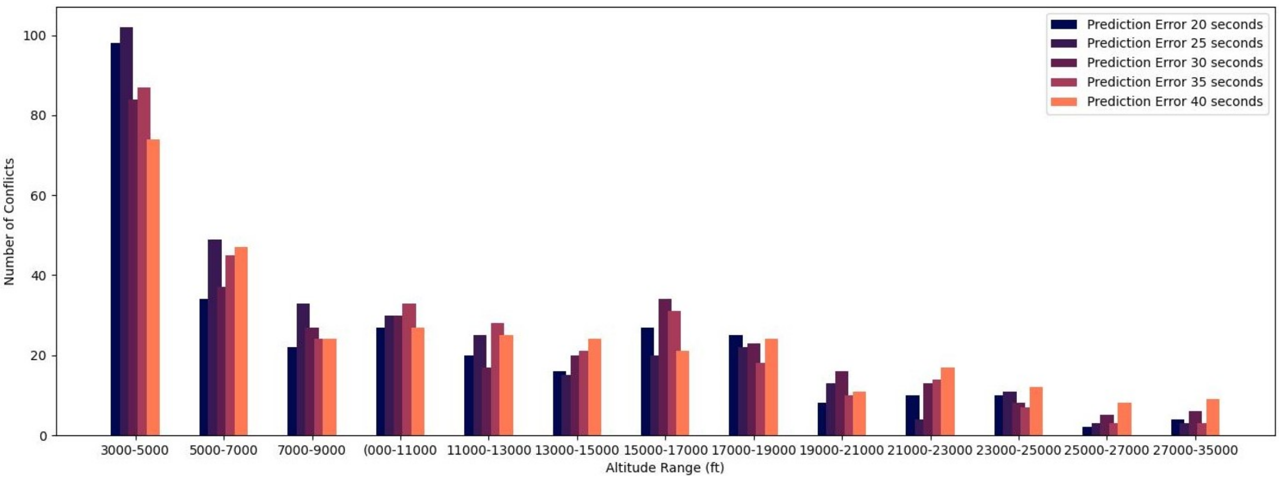

Figure 12: *Number of conflicts for different range of altitudes.*

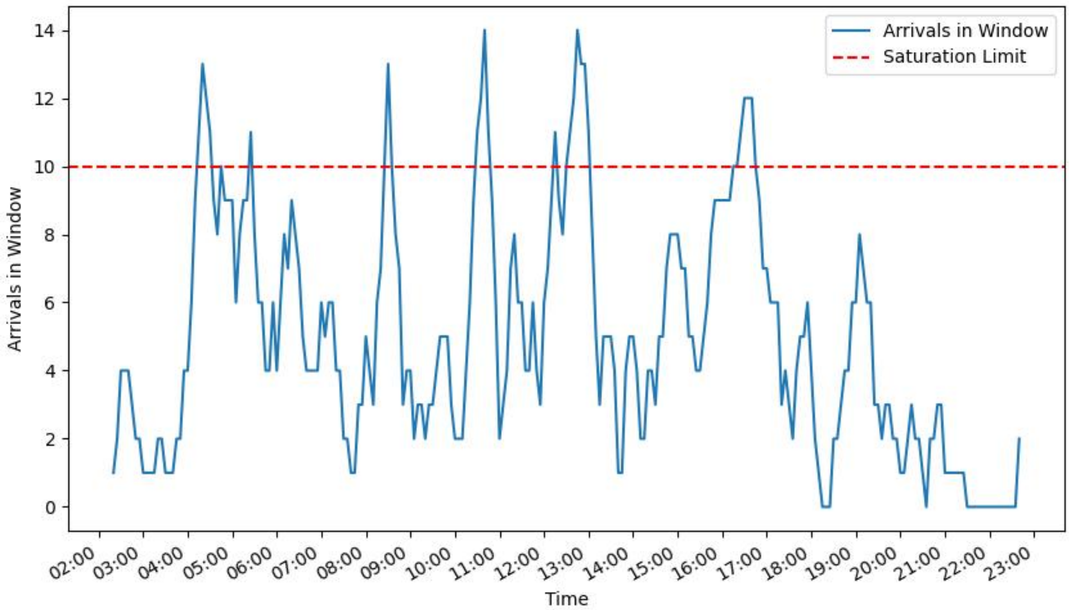

Figure 13: *A rolling window analysis for arrivals into runway 18C.*

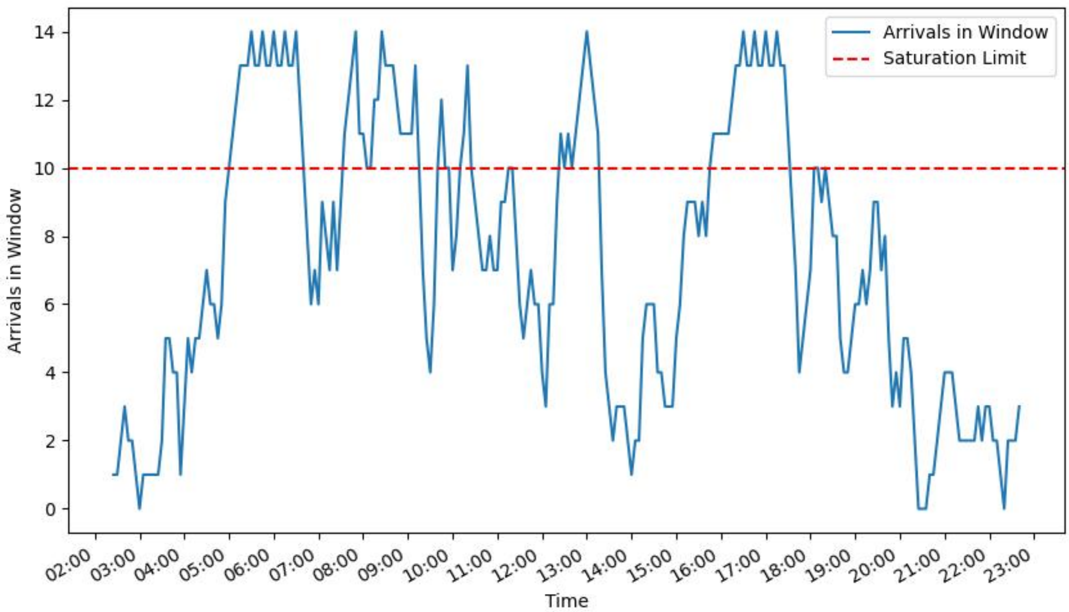

Figure 14: *A rolling window analysis for arrivals into runway 18R.*

Prediction Error (s)		No. of Conflicts	
	Run 1	Run 2	Run 3
0	182	182	182
20	222	227	224
22	229	223	225
25	243	238	239
30	248	246	235
35	251	248	255
40	264	257	268
45	250	260	266
50	256	254	269
55	270	264	272
60	271	264	266

Table 2: *Number of conflicts in the simulation for a range of prediction error for runway 18R.*

Prediction Error (s)	CDA Rate (%)			
	Run 1	Run2	Run3	Mean
0	59.73	59.73	59.73	59.73
20	50.88	49.77	50.44	50.36
22	49.33	50.66	50.22	50.07
25	46.23	47.34	47.12	46.90
30	45.13	45.57	48.00	46.23
35	44.46	45.13	43.58	44.39
40	41.59	43.14	40.70	41.81
45	44.69	42.47	41.15	42.77
50	43.36	43.80	40.48	42.55
55	40.26	41.59	39.82	40.56
60	40.04	41.59	41.15	40.92

Table 3: *CDA success rate of the simulation for a range of prediction error for runway 18R.*

Prediction Error (s)	No. of conflicts	Success Rate (%)
0	110	64.16
20	99	67.75
22	97	68.40
25	109	64.44
30	114	62.86
35	98	68.07
40	112	63.51
45	115	62.54
50	130	57.65
55	134	56.63
60	114	62.86

Table 4: *Number of conflicts in the simulation for a range of prediction error for runway 18C.*

4.2 Number of aircraft in conflict across a range of altitude

The results of analysis of how aircraft conflicts are spread across different range of altitude is as shown in Table 5. A plot of the same is as shown in Figure 12. It is observed that as the altitude decreases, the number of conflicts increase over the range of varying prediction error. An average of about 85% of conflicts occur at altitudes lower than $19000ft$ with about 40% of conflicts below $9000ft$. The most number of conflicts occur in the altitude range of $3000ft$ to $5000ft$. This is the region where aircraft converge at IAF and begin their approach to the runway.

Altitude Range (ft)	SD20	SD25	SD30	SD35	SD40
3000 - 5000	98	102	84	87	74
5000 - 7000	34	49	37	45	47
7000 - 9000	22	33	27	24	24
9000 - 11000	27	30	30	33	27
11000 - 13000	20	25	17	28	25
13000 - 15000	16	15	20	21	24
15000 - 17000	27	20	34	31	21
17000 -19000	25	22	23	18	24
19000 - 21000	8	13	16	10	11
21000 - 23000	10	4	13	14	17
23000 - 25000	10	11	8	7	12
25000 - 27000	2	3	5	3	8
27000 - 35000	4	3	6	3	9

Table 5: *Number of conflicts in the simulation for different range of altitude and prediction error for arrivals to runway 18R.*

4.3 F-test

As previously discussed, the F-test is conducted on the simulation data to interpret the implications of variations in the number of conflicts across three distinct runs. The F-test/ANOVA results, presented in Table 6, yield a f-statistic of 0.0492, signifying a low value. The corresponding p-value is 0.9519, surpassing the predetermined threshold of 0.05. The box plot depicting the distribution of the three runs is illustrated in Figure 10.

A p-value exceeding the established threshold implies insufficient evidence to reject the null hypothesis H_o. This hypothesis asserts that the variation in

	f-test
f-statistic	0.0492
p-value	0.9519

Table 6: *p-value and f-statistic after performing f-test.*

the number of conflicts among the three simulation runs is primarily attributable to random chance, and there is no systematic impact of prediction error on conflict numbers. The overlapping box plots and the low f-statistic indicate that there is no statistically significant difference between the distributions of the simulations.

5 Discussion

This section delves into a discussion of the previously presented results. It also encompasses a thorough exploration of the limitations inherent in the research work, the underlying assumptions, and outlines potential avenues for future research.

5.1 Result

The outcomes of the simulations and the analysis conducted in the experiment to assess the influence of prediction accuracy on the success rate of CDA were presented in the previous section. It was observed that, for runway 18R, the number of conflicts increases as the prediction error rises. This aligns with the research hypothesis. This behavior could be attributed to the fact that, with an increase in prediction error, more randomness is introduced into the system, consequently raising the chances of aircraft having conflicting paths. A noticeable trend was the decrease in the mean CDA success rate from 59.73% to approximately 40% when the prediction error reached 60 seconds. The variation in the mean CDA success rate with increasing prediction error is noteworthy. An intriguing observation is the plateau observed after 40 seconds of prediction error, where the decline in the mean success rate is not as substantial as the decrease observed between 0 and 40 seconds. This phenomenon could be attributed to the scenario during an arrival peak when the traffic density is high. If all potentially conflicting aircraft are already in conflict, further increases in randomness may not result in additional conflicts, as there are no remaining aircraft to be in conflict with. To comprehend this behavior more thoroughly, a more in-depth analysis should be conducted.

The results for runway 18C contrasted with those for 18R. Notably, the prediction error seemed to have no discernible impact on the number of conflicts, and the success rate of CDA consistently hovered around 62%. The outcomes of the rolling window analysis revealed that the duration during which runway 18R exceeded or equaled the saturation limit of 10 aircraft per a 20-minute window was significantly higher than the corresponding period for runway 18C. The observed variation could be attributed to a greater number of arrivals from sectors 3, 4, and 5 for runway 18R compared to sectors 1 and 2, resulting in a lower traffic density at runway 18C. Consequently, despite the introduction of randomness into the system, the configuration of aircraft arrival was likely such that it exerted a minimal influence on conflict paths, primarily due to the lower overall traffic density for arrivals into 18C. A more in-depth analysis of this behavior is required for a comprehensive understanding.

An examination of the number of aircraft conflicts across different altitude ranges revealed a substantial increase in conflicts as the altitude decreased. Specifically, approximately 40% of the total recorded conflicts occurred below 10,000 feet. This trend might be associated with aircraft converging at the IAF at lower altitudes as they initiate their approach into the runway, coupled with the fact that aircraft tend to fly at slower speeds at lower altitudes. However, it is essential to conduct a more comprehensive and detailed study to thoroughly understand the relationship between altitude and the occurrence of conflicts. The results of the F-test reveal a low f-statistic value of 0.049 and a very high p-value of 0.9519. Both of these parameters suggest that there is not enough evidence to reject the null hypothesis. The null hypothesis states that the variation in the number of conflicts across the three simulation runs is solely due to random chance, and there is no systematic effect of prediction error on the number of conflicts. In other words, there is no statistically significant difference between the distributions of the three simulations. This implies that it can be reasonably assumed that the simulation, when run any number of times, would behave in a similar manner as it did during these three runs.

5.2 Limitations and Assumptions

The current study has inherent limitations that warrant acknowledgment and consideration for a more nuanced interpretation of the research findings, paving the way for future investigations into the impact of trajectory predictability on aircraft operations. For this research it is assumed that the relevance of weather data is not high as this can be reproducible. The simulations were exclusively conducted on the air traffic management simulator, BlueSky, which, while offering high fidelity, is not without its own set of limitations. Notably, the aircraft performance models, though advanced, may still be refined for increased realism and accuracy.

A notable limitation arises from the current constraints imposed by the aircraft performance model, which limited the arrival manager database to speeds ranging from 200 knots to 270 knots. Ideally an upper

limit of 310 knots is preferred. To address this constraint, future developments could involve expanding this speed range, enabling the inclusion of higher speeds in the database. Such an enhancement would grant ATC greater flexibility in managing speed targets, thereby bolstering the overall robustness of the study.
Moreover, the reliance on historic data comprising a single day's arrivals, totaling approximately 758 aircraft, was dictated by computational constraints. To enhance the robustness of the results, expanding the date range could be considered if computational resources permit.
The assumption made that the weather data is irrelevant for this study needs more scrutiny. While easily reproducible, the validity of this assumption remains uncertain. A comprehensive evaluation is essential to understand how weather factors may influence the relationship under investigation.

5.3 Recommendations and Future works

Future research within the scope of understanding how prediction errors affect continuous descent approaches could involve using an updated aircraft model with an advanced algorithm to incorporate the Mach-CAS speed schedule. Additionally, investigating the influence of weather conditions would contribute to a comprehensive understanding of the complete impact of prediction errors on trajectory-based operations. While this study focused on a specific runway combination, 18C and 18R, there is potential for exploring additional runway combinations to assess their performance and gain further insights.

6 Conclusion

The primary goal of this research was to evaluate the impact of prediction error on the successful execution of continuous descent approaches in a high-traffic density condition at Amsterdam Schiphol Airport. The study presents promising evidence suggesting that there is a significant improvement in implementing CDA when prediction errors are reduced.
Nevertheless, it's important to note the presence of certain assumptions and limitations in the study's methodology. These factors should be considered with a degree of caution when interpreting the results, as they introduce complexities to the overall understanding. Despite these considerations, the findings contribute substantively to our comprehension of how prediction errors impact CDA, offering a nuanced yet comprehensive view of the behaviour. Furthermore, this research lays a foundation for future studies in the field. The insights gained from examining the influence of prediction errors on CDA not only contribute to the current understanding but also provide a starting point for further investigations. Future research endeavors can explore additional aspects related to CDA dynamics and delve into potential refinements for more accurate predictions, contributing to the ongoing advancement of air traffic management practices.
Moreover, this research offers a compelling rationale for airlines to consider investments in equipping their fleets with ADS-C ATN-B2 systems. The findings suggest that these technological advancements not only contribute to the overall enhancement of CDA efficiency but also make a persuasive case for optimizing air traffic management. As such, this study stands as a substantive resource for aviation stakeholders, providing both theoretical insights into the correlation between prediction error and CDA, and acting as a foundation for future conversations where the persuasive value can be leveraged to encourage the adoption of advanced surveillance and communication systems, specifically the ADS-C ATN-B2, within the airline industry.

References

[1] EUROCONTROL. *Automatic Dependent Surveillance Contract (ATS-B2)*. `https://www.eurocontrol.int/service/automatic-dependent-surveillance-contract-ats-b2`.

[2] KDC-CoE Mark Eijkens. *"Analysis of Vertical Flight Trajectory Efficiency"*. `https://kdc-mainport.nl/2018/08/15/kdc-final-thesis-marc-eijkens/`.

[3] EUROCONTROL. *U.S./Europe comparison of air traffic management-related operational performance for 2017*. `https://www.eurocontrol.int/publication/useurope-comparison-air-traffic-management-related-operational-performance-2017`.

[4] Airbus. *4D-TBO: a new approach to aircraft trajectory prediction)*. `https://www.airbus.com/en/newsroom/stories/2020-12-4d-tbo-a-new-approach-to-aircraft-trajectory-predictionmatic-dependent-surveillance-contract-ats-b2`.

[5] EUROCONTROL. *Automatic dependant surveillance contract enables and supports improved ATM operations*. `https://www.eurocontrol.int/project/automatic-dependant-surveillance-contract-enables-and-supports-improved-atm-operations`.

[6] EUROCONTROL. *Consultation - Draft EUROCONTROL Specifications on ATS B2 datalink common services and SWIM ground distribution*. https://www.eurocontrol.int/publication/consultation-draft-eurocontrol-specifications-ats-b2-datalink-common-services-and-swim.

[7] SESAR. *Extended Projected Profile (EPP) availability on ground*. https://www.sesarju.eu/sesar-solutions/extended-projected-profile-epp-availability-ground.

[8] Paul Mark Alexander De Jong. "Continuous descent operations using energy principles". In: (2014).

[9] Joost Ellerbroek, Mazin Inaad, and Jacco Hoekstra. "Fuel and emission benefits for continuous descent approaches at Schiphol". In: *2018 International Conference on Research in Air Transportation (ICRAT2018)*. 2018.

[10] John-Paul B Clarke et al. "Continuous descent approach: Design and flight test for Louisville international airport". In: *Journal of Aircraft* 41.5 (2004), pp. 1054–1066.

[11] Kars ter Beek. "High capacity Continuous Descent Operations: A case study of Amsterdam airport Schiphol". In: (2022).

[12] Bart Bouwels. "Off-Idle Continuous Descent Operations at Schiphol Airport (SARA)". In: (2021).

[13] Joost Ellerbroek Jacco Hoekstra. *BlueSky Open Air Traffic Simulator*. URL: https://github.com/TUDelft-CNS-ATM/bluesky/wiki. (accessed: 01.09.2016).

[14] TU Delft LVNL. *"InnovationLabs: A joint venture between LVNL and Delft University of Technology"*. https://www.lvnl.nl/over-lvnl/innovationlabs.

[15] SESAR. *LARGE SCALE DEMONSTRATIONS PROJECT PJ38-W3-ADSCENSIO - ADS-C Enables and Supports Improved ATM Operations*. https://www.sesarju.eu/projects/ADSCENSIO.

Part II

Preliminary Report

(Already graded as a part of Literature Study AE4020)

1
Introduction

Airports that have high traffic movements such as Amsterdam's Schiphol are in constant search for methods that help improve their efficiency. One of the important areas of focus for airports are departure and arrivals. The goals of such busy airports is to improve their arrival capacity as much as possible which in turn leads to an increase in revenue. This means that they need to constantly research and adapt new techniques and methods.

One such future concept for arrivals at Amsterdam Schiphol Airport, as for many airports, is to progressively implement Continuous Descent Operations (CDO). For this, it is already known that a high degree of predictability of the arrival trajectories is needed. One key parameter used to determine the arrival trajectory is to have time prediction at Initial Approach Fix (IAF) as accurately as possible. Research has shown that the quality of the Time Prediction can be improved by leveraging information from the aircraft. With new Air Ground Datalink (AGDL) technology emerging, specifically ADS-C from Baseline 2 datalink, these possibilities are becoming within reach. However, it is unclear to which extent the integration of this AGDL provided information will enhance the time prediction. Moreover, the sensitivity of the managed arrival process to the predictability of the trajectories, both in the prediction as well as the execution phase of the arrival is unclear.

Having a better insight in this dependency enables the further design of the technical concept by providing target performance levels. In turn, it also provides direction and input to the business case for equipage by airlines for trajectory sharing as well as ground system trajectory prediction performance. To establish a useful measurement for value added by improved predictability of the success rate, that is, the percentage of CDO's that can be executed without ATC intervention, is envisioned.

In order to improve the time prediction accuracy using the AGDL, this research project is to develop a model of advanced arrival management in which the effect of varying time prediction can be measured in terms of percentage of flights that can execute a full and partial CDO procedures.

This report is structured as follows. Chapter 2 defines the research objective of this thesis and establishes the research question. Followed by Chapter 3 which provides background and information on continuous descent operations and the current operational problems in detail. It also explains the definitions of terms used for this research project. Chapter 4 explains the methodology and important concepts required for this research. Chapter 5 gives more details about the research proposal, the limitations of this study and the assumptions made. Chapter 6 concludes this report and gives a status update of the work and the further steps that needs to be carried out. A Gantt chart is attached in the appendix that highlights the research plan in terms of dates.

2
Research Objective

The motivation for this research and the research objective and the research question is established in this chapter.

2.1. Motivation

As previously mentioned, Amsterdam Airport (AMS) must continually embrace innovative approaches to enhance its capacity. One effective strategy involves implementing Continuous Descent Approaches (CDAs) during periods of high traffic density. However, the hindrance to executing CDAs in these scenarios lies in the lack of critical information available to ground controllers, such as aircraft mass and performance. Consequently, controllers are not involved in the trajectory calculations. The current unavailability of essential information poses a barrier to the implementation of CDAs during high-density operations at AMS. To address this challenge, the introduction of systems like Automatic Dependent Surveillance - Contract, particularly Extended Profile Projection (EPP) from Aeronautical Network: baseline 2 (ATN-B2), facilitates the sharing of vital information, paving the way for improved trajectory management. This research is conducted to analyze the impact of prediction accuracy on the successful implementation of a Continuous Descent Approach (CDA).

2.2. Research Objective

The future paradigm for arrivals at Amsterdam Schiphol, akin to many airports, involves the gradual implementation of Continuous Descent Operations (CDO). It is recognized that achieving a high degree of predictability in arrival trajectories is crucial for successful CDO implementation. Previous research indicates that enhancing the Trajectory Predictor's (TP) performance is possible by incorporating information from the aircraft. The emergence of new Air Ground Datalink (AGDL) technologies, particularly ADS-C from Baseline 2 datalink, offers opportunities in this regard. However, the extent to which integrating AGDL-provided information enhances TP performance and the sensitivity of the managed arrival process to trajectory predictability remain unclear.
Gaining a better understanding of this dependency is essential for refining the technical concept, establishing target performance levels, and providing guidance for the business case associated with airline equipage for trajectory sharing and ground system trajectory prediction performance. To measure the value added by improved predictability of the success rate — expressed as the percentage of CDOs executed without Air Traffic Control (ATC) intervention — a useful metric is envisioned. This endeavor aims to inform the further development of the technical concept and enhance decision-making processes related to trajectory sharing and prediction performance.

2.3. Research Questions

The following research question is formulated based on the research objective:

"How does varying the time prediction accuracy in the arrival process of aircraft at Amsterdam Schiphol

Airport in high density situation affect the ability for executing continuous descent approach procedures successfully?"

This research question can be further divided into sub-questions which can be formulated as follows:

- What is the relation between time prediction accuracy and flights executing continuous descent approaches?
- What effect does different levels of top of descent (TOD) have on the time prediction accuracy?
- To what extent does successfully performing CDAs relate to the performance of arrival capacity?

2.4. Research Project Stakeholders

This research is focused on establishing a relation between executing successful CDO and time prediction accuracy to perform this successful CDO. The outcomes from this research thus has several stakeholders with their interests.

- LVNL
  The ANSP can use this knowledge of how integrating AGDL into inbound planning affect in executing CDOs and how the capacity of arrivals could potentially be increased.
- Aircraft Operators
  The airlines can use the knowledge of this research to understand the justification of investing in equipping their aircrafts with air ground data link equipment's that transmit critical data to the ground constantly.
- General Public
  The potential improvement in successful CDO would imply low fuel use which implies lower emissions and less noise emitted which would benefit the general public.
- Scientific Community
  This research can be a stepping stone for further research on how the approaches can be made more efficient and also investigate the effect of AGDL data and its feasibility

2.5. Hypotheses

With the research question defined, it can be hypothesised that:

- By increasing the prediction accuracy of the trajectory the number of CDAs flown increases because by having a more accurate aircraft trajectory the number of aircraft in conflict paths would decrease which would mean there is less intervention from the air traffic controller. As the prediction error increases the number of conflicts would increase thus the rate with which a CDA can be executed would decrease.
- It can also be expected that as the altitude decreases, the number of conflicts would increase because at lower altitudes the speeds are lower and the traffic is converging towards the runway which would mean increase in aircraft traffic density thus more chances of conflicts.

3 Background

This chapter provides the reader with an introduction to the literature. It explains the phases in arrival in detail, the different kind of approaches and more information about operational background of Continuous Descent Operations(CDO), with the purpose of identifying a research gap and thus determining what analyses ought to be undertaken. First, Section 3.1 introduces the general concept of aircraft operations, describing the phases involved in a flight. Secondly, Section 3.2 describes the types of approaches that exist at AMS schiphol Airport and their differences.

3.1. Flight Phases

Any given flight that is ready to depart for its destination from its origin, can basically be divided into three distinct operational phases as shown in 3.1.

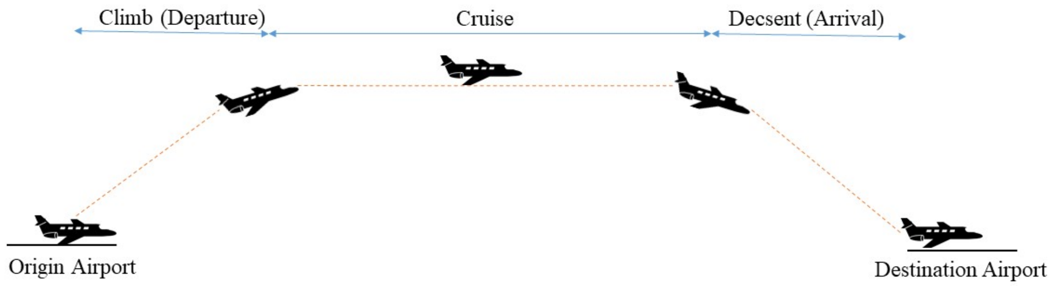

Figure 3.1: Different Phases of a commercial flight

The climb phase, the cruise phase and the land phase. During the climb phase, the aircraft is predominantly in contact with the departure part of the ANSP. During the cruise phase it is in contact with area control part of the ANSP. During the Descent, it is in contact with approach and tower part of the ANSP.

It is a known fact that many airports and hubs are operating at almost full capacity due to a steady increase in air traffic density over the years in Europe [8]. Although this has currently reduced due to Covid and its aftereffects, the flight traffic is almost reaching back to pre pandemic levels. This means that there's more pressure on ANSPs to balance the assigned time slots for flights planned while maintaining the required high level of safety and to respect the regulations present with respect to noise and emissions. Which means the aircraft must leave and return to the ground as quick as possible to reduce noise and with efficient engine settings to satisfy the emissions parameters. This already is the case with takeoff, where the aircraft is given instructions to climb as quickly as possible to reach higher altitude to make less noise in the vicinity also known as noise abatement procedures. Thus the attention is now moved to the approach phase. This phase has been using the same navigational aids for a long time now which encompasses of instruments such as the Instrument Landing System (ILS), Very high frequency omni-directional Range (VOR), Distance Measuring Equipment (DME) and such. But with the amount of advancement in technology and the highly increasing capabilities of the Flight Management System (FMS) which enables the aircraft to execute more complex procedures are seldom used.

3.2. Approach Procedures

Approach procedure can be described as the profile the flight follows both laterally and in altitude from the point of its initial descent, called Top of Descent (TOD), till it reaches the runway surface. Generally, every airport has a specific sets of arrival routes called the Standard Terminal Arrival (STAR) Procedures. These are like specific preset highways in air. But the descent profile that an aircraft can follow flying a specific STAR can be flight specific. During high traffic density operations at Amsterdam Schiphol Airport, every aircraft is vectored individually by the ATC. Although the vertical profile of the approach can be unique to a flight, it can be classified in a broader sense. There are various kinds of vertical profile of approach procedures. The two predominant ones are namely Stepped approach as explained in 3.2.1 and Continuous Descent Approach profile as explained in 3.2.2.

3.2.1. Stepped Approach

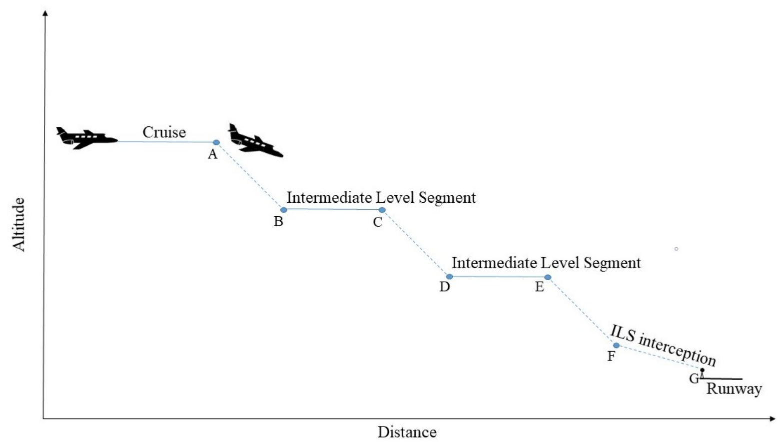

Figure 3.2: Stepped Approach profile

It is a common approach procedure used in most airports worldwide where an aircraft is given an altitude to maintain until a new lower altitude is given by the ATCs. It is as shown in Figure 3.2. It can be observed that the aircraft descends in steps. It is to be noted that to fly in segments between points B-C, D-E and various such level segments, the aircraft needs to increase its thrust settings considerably. This can be attributed to the thrust required to maintain the speed with extended flaps and to the fact that aircraft needs more thrust to fly level in air as compared to descending down. This means that the pilots use aggressive variable thrust settings to maintain this stepped flight path of the aircraft. A stepped approach is generally used in airports during high traffic density approaches as a stepped approach gives ATC more control over traffic.

3.2.2. Continuous Descent Approach

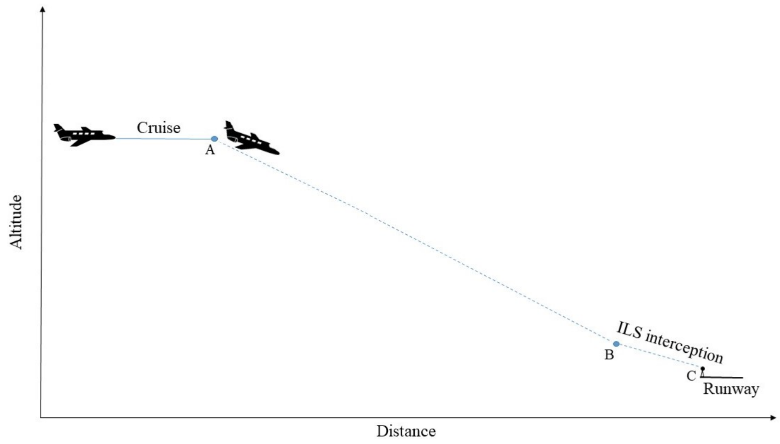

Figure 3.3: Continuous Descent Approach Profile

Continuous descent approach can be explained as the flight profile of an aircraft that starts its decent from its cruise level, and then fly's in one smooth downward motion towards the runway. It is as shown in Figure 3.3. It can be observed that the aircraft starts its decent from TOD at point A, and then flies down to point B where the ILS can be intercepted without any intermediate level segments. This approach is generally used when the traffic density is not high. The need for ATC to constantly worry about the trajectory of aircraft is less.

3.3. Comparison between stepped and continuous descent approaches

A comparison of the vertical flight path of both the approaches can be plotted as shown in 3.4

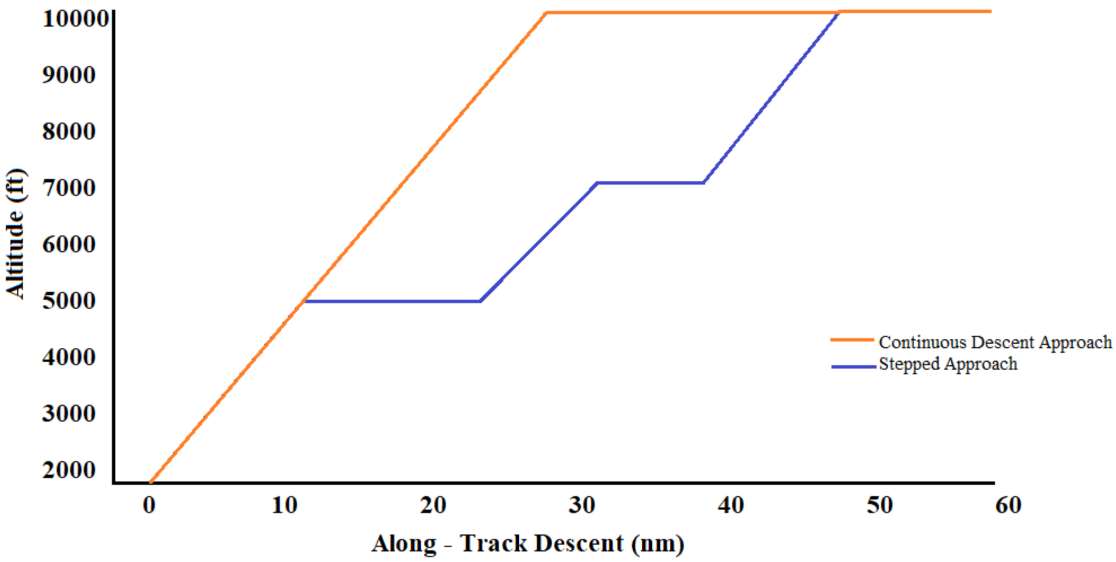

Figure 3.4: Comparison between flight paths of a stepped approach and continuous descent approach

Various researches have been conducted in evaluating both the stepped approach and the continuous descent approach. It can be said with sufficient scientific backing that CDAs are better than stepped approaches with respect to a lot of parameters [5]. One major parameter in the aviation industry is the fuel consumption. There are various variations in CDA when it comes to the fuel settings used. These are mainly off idle settings and ideal fuel settings.

3.3.1. CDO to save fuel burnt

In the research of [7] where the CDO is executed from any start flight level and ideal thrust conditions , it is observed and concluded that there is significant amount of fuel saved by executing CDOs. For an airbus 320 family, it was calculated that $3.51*10^6$ kg of fuel is saved per year. This study considered a fuel-optimal flight path angle. Now it can be argued that in actual operations, often off idle conditions exist. The research in [2] explores executing CDO in off idle conditions. The research also concludes that CDO with an off idle flight path angle that majority of the CDOs executed offered enormous advantages over the stepped approach procedures. CDO can also be used as a noise abatement procedure. This can be attributed to the fact that there's no rapid change in thrust settings and there's no altitude level patterns that tend to be closer to the ground.

3.3.2. CDO as a noise abatement procedure

Research in [3] explores CDO as noise abatement procedure at Louisville International Airport. The research was evaluated with an actual flight demonstration test which proved that CDO was statistically better than conventional approaches for noise abatement. It further goes on to conclude that there would be a 7 percentage of 50 Day and Night Average Sound Level contour shrinkage if all aircrafts performed CDO at thee airport.

3.3.3. CDO in high density capacity

There's also research done in [1] on CDO specifically at Amsterdam Schiphol Airport during arrival peaks which support previous studies that performing CDO even during maximum capacity situations result in savings in fuel burnt. [1] also examines the limitation and consequences of such operations.
As stated before, the ANSPs in Europe are facing difficulty in satisfying the increased airline efficiency and reduced environmental impact. A SESAR project was setup by the European Commission to move to a new air traffic management concept based on predictability of flight operations and optimization of airline operations. [12] does similar research but at congested airports in the united states and found similar results.

3.4. Current operational procedure at AMS

Currently, aircrafts flying to Amsterdam airport are monitored and controlled predominantly by LVNL. In general , inbound schiphol traffic flows from the area of responsibility (AoR) of an adjacent centre via an Amsterdam ACC-controlled area (sector) to the Schiphol APP- controlled Schiphol TMA. The ACC controllers transfer inbound traffic to the schiphol APP at the initial approach fix (IAF) located near the boundary between the ACC sector and the Schiphol TMA as shown below in figure 3.5.

Figure 3.5: Traffic Flow Diagram for AMS Schiphol

In the figure3.6 the traffic flows from left to right. The planning of the inbound flow is however from the right to left. The figure highlights the major points for an aircraft that is scheduled to land at Amsterdam airport. The inbound flow is planned by assigning a flight to a particular runway and building a landing sequence based on the landing interval per runway. Now, this runway selection can vary on the actual plan filed by the aircraft, or the current runway configuration used. An arrival Manager or AMAN as explored in [6] schedules the aircrafts based on a few requirements and criteria. What an arrival manager does basically, is to generate a list of aircraft with its scheduled time of landing on the runway which is called the landing sequence. This is done in a reverse direction of the flow of the aircraft. In the sense, First, the current landing interval of the runway is determined. This can

vary depending on the current delay the airport is experiencing, the weather conditions or various other restrictions. The maximum arrival arrivals is currently limited to 40 arrivals per hour, since each aircraft needs to be 120 seconds apart. Once an landing interval is arrived at, a flight is allocated the runway for a specific time. Now with this allocated runway arrival time, an expected arrival time is calculated. Expected Arrival Time is the time that aircraft is expected to be at the initial approach fix. Initial approach fix is a point in the STAR where the aircraft has descended enough and is at the point where it now needs to make an approach to the runway. From this point, the descend is generally linearly downwards till the runway. Thus this point is chosen for a handover of aircraft between Amsterdam Area Control (ACC) to Amsterdam Approach (APP). Understandably this is a crucial point for air traffic management in Amsterdam arrivals. This Expect Arrival Time is calculated 12 minutes prior to the time that aircraft is scheduled to arrive at the initial approach fix. This is the target delivery times for the ACC controllers. Now, the ATC's can intervene and speed up a flight to absorb a delay, or delay a flight that's early such that the aircraft is delivered at the IAF within a margin of 120 seconds.
From this landing slot for each flight a time is calculated at which the flight is expected to enter the TMA at the IAF. This Expected Approach Time (EAT) is calculated 12 minutes before the flight is expected to arrive over the IAF. The EAT is used by Amsterdam ACC as a target time to deliver inbound flight to schiphol within a margin of two minutes of the EAT. In addition, there are restrictions at the IAF on flight level and speed for flights that are transferred from ACC to APP.

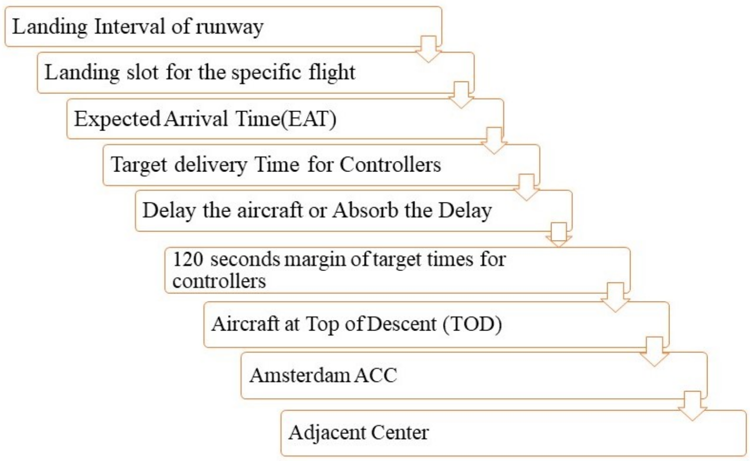

Figure 3.6: Steps for an aircraft arrival at Amsterdam Airport.

Currently, the ATCs use their intuition to deliver an aircraft at the IAF with the required EAT. This is done by using radar vectoring and or speed changes.The Concept of this research is to come up with a concept similar to NASA's EDA [4] and LVNL's own tool called Speed and Route Advisor (SARA)[10]. SARA comes up with a speed advise , a route advice, or a speed and route advice to deliver an aircraft at IAF with a margin of 30 seconds of EAT.

The addition being, this research uses ADSB-C data to improve the predictability of the TP and thus enabling successful CDO. The Basic Concept of the working of this tool is presented below.

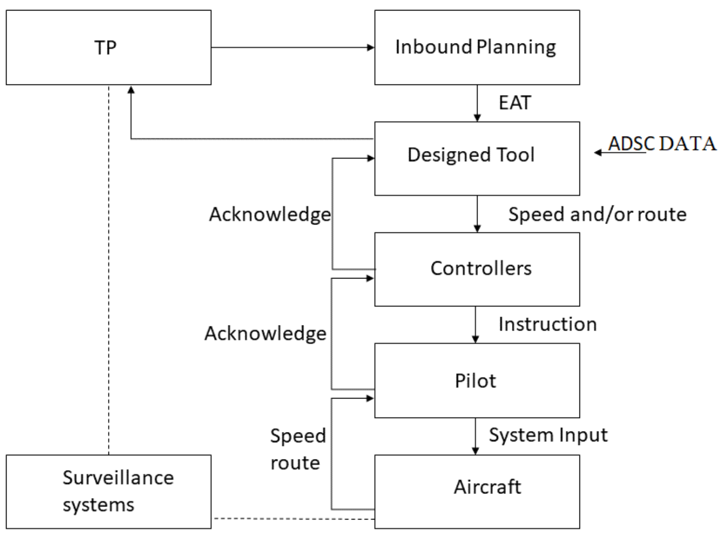

Figure 3.7: Diagram depicting the working of various entities during an approach

4
Methodology

This chapter describes the methodology used to perform the research plan that was discussed in the previous chapter. It must mentioned that the two research questions stated in the previous chapters are interconnected.
This chapter is structured as follows. Firstly, TP and an arrival manager needs to be modelled such that the experiments can be run. The next step would involve injecting AGDL noise into this TP and looking at its performance.

4.1. Simulation Framework

The basic outline to answer the second research question is as shown below in Figure 4.1. The steps are explained further in brief in this section.

Figure 4.1: Workflow Process

4.1.1. Model a simple Arrival Manager

The simulation software also lacks an arrival manager. Arrival Manager is simply a tool that determines the sequence in which aircraft must be delivered at the IAF. A simple research Arrival Manager thus needs to be modelled for the scope of this research. It is crucial to clarify that the primary objective of this research is not to quantify the impact of Air-Ground Datalink (AGDL) on Trajectory Predictor (TP) accuracy. Extensive research on this aspect has already been conducted, as evidenced by studies such as the one carried out by the Single European Sky ATM Research (SESAR) project [13]. The SESAR project's findings have conclusively demonstrated that integrating AGDL into the TP results in improved accuracy.
An arrival manager is to be modeled to generate a sequence of arrivals into a runway, spacing the aircraft at 90-second intervals. This specific spacing, referred to as the inter-availability time, is in line with the operational standard set at Amsterdam Airport Schiphol (AMS).

4.1.2. Baseline Simulation

A baseline simulation is created, modeling the arrival of aircraft at a specific runway. The simulation records the number of aircraft conflicts, serving as a benchmark for comparison with other simulations.

4.1.3. Simulation with Prediction Error

After establishing a baseline, the system is introduced to randomness by altering prediction accuracy, achieved through changes in the spawn time of aircraft. The resulting number of aircraft conflicts with varying prediction errors is recorded for comparison with the baseline, enabling further statistical analysis.

4.2. Simulation software : BlueSky

BlueSky [9] stands out as an open-source, user-friendly air traffic management simulator renowned for its high fidelity. Widely embraced in numerous research endeavors, BlueSky offers capabilities for simulations and verification. The software allows the creation of air traffic scenarios through scenario files that can be seamlessly loaded into the program. Notably, it can simulate actual flight paths using historical data by integrating BADA (Base of Aircraft Data) into its framework.

BlueSky provides the ability to exert control over aircraft using various commands, mimicking real-life scenarios, and supports real-time simulations. Originating with the primary goal of establishing a versatile tool for comparisons in air traffic management (ATM), BlueSky has successfully fulfilled this purpose. The version of BlueSky utilized in this research is sourced from Innovations lab [11], chosen for its specific focus on customizing BlueSky with proprietary data tailored for Amsterdam Airport Schiphol (AMS). The graphical user interface of this version is depicted in Figures 4.2 and 4.3.

To ensure precise replication of aircraft performance within the simulation, the ATM simulator relies on a dedicated aircraft performance model. For this study, the selected model is obtained from iLabs and is specifically designed for evaluating aircraft performance within traffic destined for Amsterdam Airport Schiphol (AMS). Crafted using proprietary data from iLabs and its collaborators, this model is intricately tailored to closely emulate the actual traffic performance into AMS, rendering it particularly well-suited for the objectives of this research.

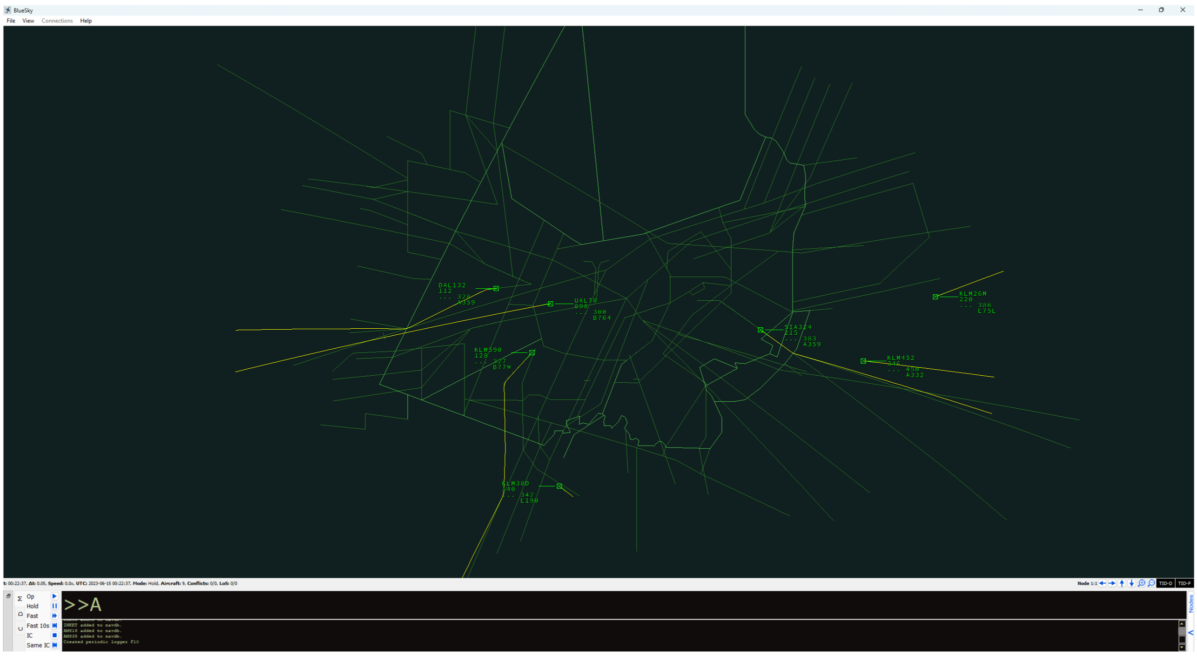

Figure 4.2: GUI of BlueSky [9]used in Innovationlabs [11]

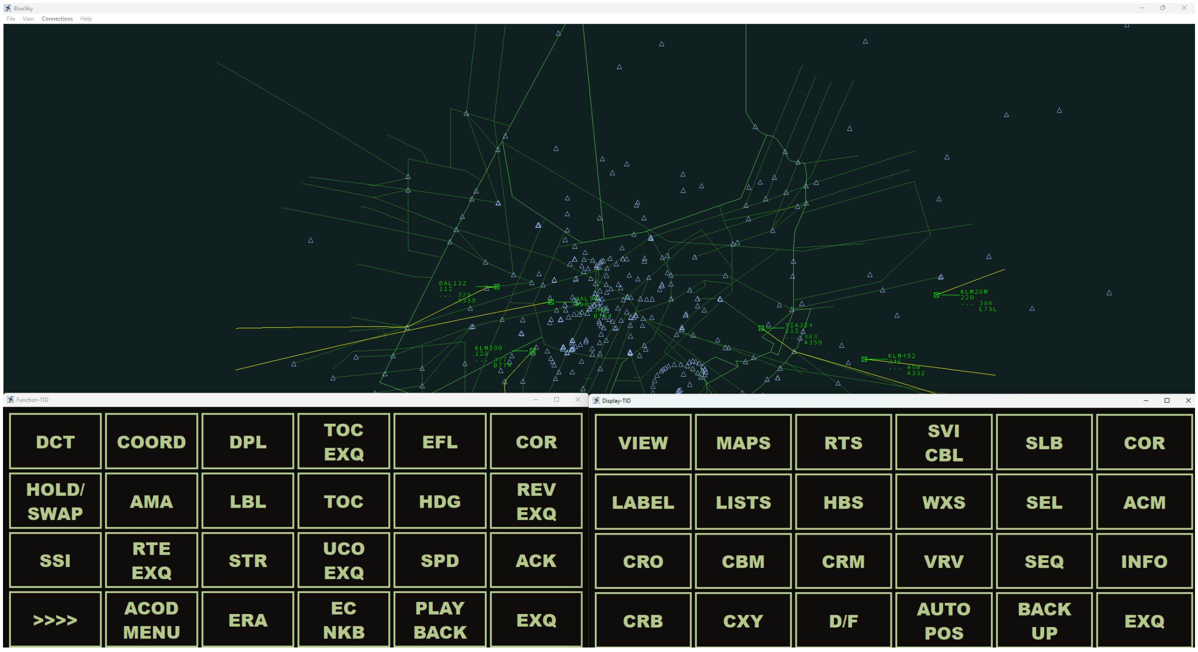

Figure 4.3: Various control inputs [11] that can be fed into the software [9].

5
Research proposal

For a research project to be successful, a good scope is required. This is because with a proper scope, it can be established that the research is focused, realistically planned and is executable. A detailed background was explained in the previous chapters. This chapter deals with application of knowledge from previous chapters into setting up this research.

5.1. Research performed

This research uses the ”Black box approach to try to answer the research questions previous established. Black box approach is an approach, where the input and the output is known to the user, but the intermediate understanding needs to evaluated. In this research it can be shown as in Figure 5.1. The aim of this research is to understand the relation between the prediction error and CDO. But the end result would be to increase the traffic flow capacity into Amsterdam Airport. This is what is illustrated in the figure.

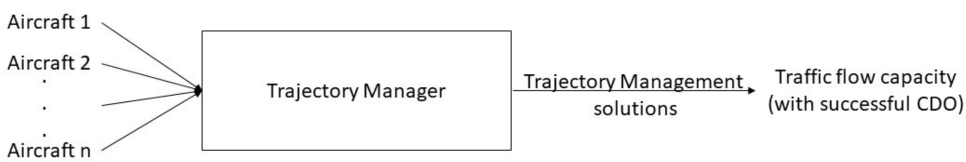

Figure 5.1: TP flow diagram

5.2. Phases of this research

To address the research questions posed in the previous sections, this thesis can be segmented into distinct phases, as depicted in Figure 5.2.

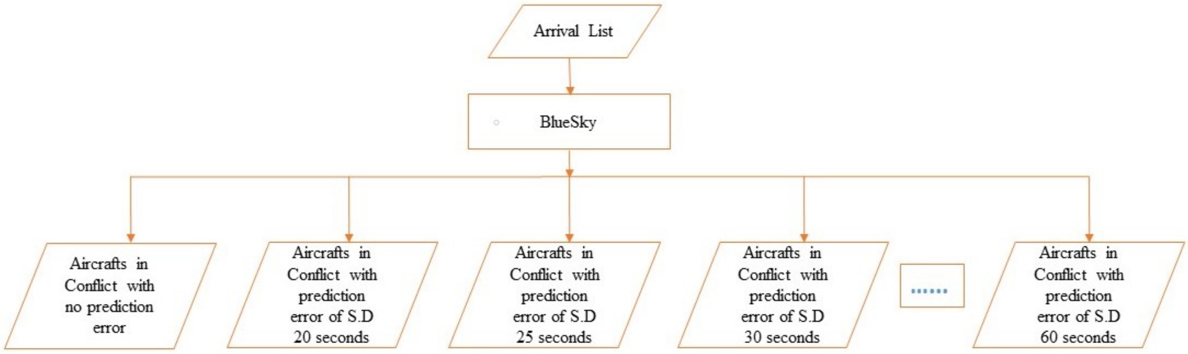

Figure 5.2: Phases of this research

The initial phase involves obtaining a baseline, which serves as a reference for comparison with the modeled experiments. Subsequently, a function is formulated to define the successful Continuous Descent Operation (CDO) rate. Simulations are then conducted, introducing varying prediction errors as noise. This noise is quantified in terms of standard deviation, introducing randomness into the system concerning its arrival time at the runway threshold. The general flow diagram depicting the process of running both a baseline simulation and simulations with varying prediction errors is illustrated in Figure 5.3.

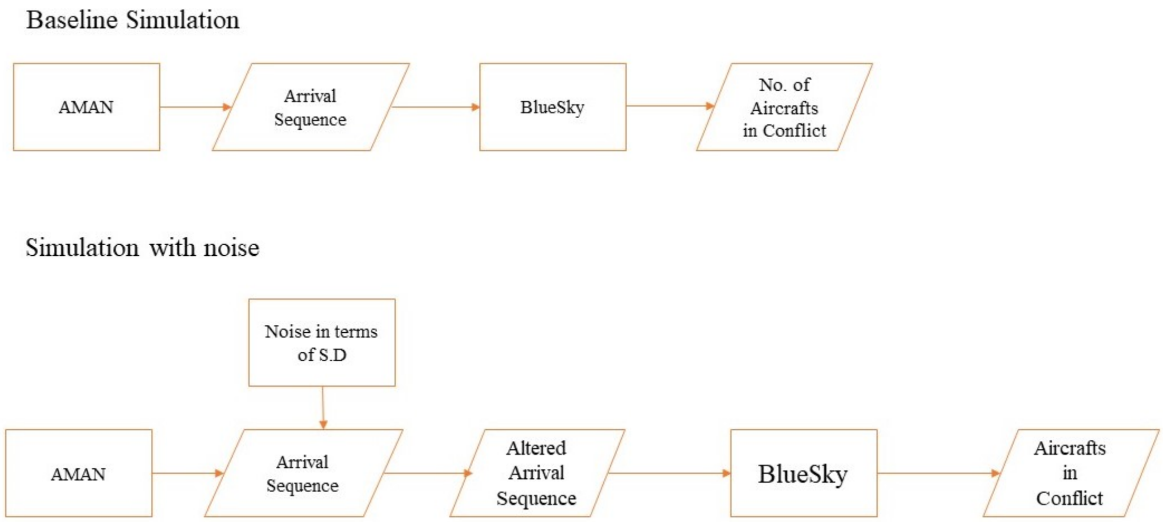

Figure 5.3: Simulation work flow.

5.3. Experimental Setup

The experimental setup to perform this research is explained in this section.

5.3.1. Model

The experimental setup for this work is outlined below. As mentioned earlier, the experiment utilizes BlueSky [9], which operates on Python. Simulations are input into BlueSky in the form of ".scn" files (Scenario Files), which serve as the intrinsic input for the software. While these scenario files are essentially written in Notepad, they employ commands specific to BlueSky. Scenario files function as detailed instructions for creating, flying, and landing an aircraft. They can be modeled to operate on BlueSky's autopilot using commands like waypoints, or defined using coordinates. A sample ".scn" file is provided in the appendix A.1, demonstrating its use to simulate actual historic flight routes flown in August of 2020. For analysis and various other computational tasks, Python is employed. The computational resources and processing time for these simulations are not a significant concern, as this setup is not live or GUI-based. It primarily processes historical data and simulations in BlueSky that are not time-restricted. The designed model is open source, subject to approval from stakeholders.

5.3.2. Variables

The independent variable for this experiment is prediction accuracy, measured in seconds. The dependent variable is the percentage of successful Continuous Descent Operations (CDOs). To establish what constitutes a successful CDO, a definition will be provided shortly. An intermediate variable, the number of aircraft in conflict, is introduced to gauge the success rate of CDOs. This variable represents the count of aircraft in conflict during the simulation.

5.3.3. Assumptions and Definitions

These following assumptions are made for this research;

- It is assumed that the effect of wind is out of scope for this project as this is easily reproducible when it is fed into a normal working TP.
- It also assumes that the aircraft model present in BlueSky by default is highly accurate enough.
- In real world, off idle continuous descent is more achievable and is beneficial enough as compared to idle CDOs.

The following definition is of utmost importance: Defining a successful CDO. A successful Continuous Descent Operation for this research is defined as:

- a CDO performed without any radar vectoring.
- a CDO that has no level segments between the Top of Descent till the Initial Approach Fix.
- a CDO where speed manipulations is still allowed.

When a conflict occurs, if the ATC intervention is in terms of anything other than speed changes then it is not a successful CDO. Which is why understanding the speed advisories from SARA was important.

5.3.4. Data

In this research endeavor, the significance of both the quality and quantity of data cannot be overstated. The study is conducted at the Knowledge and Development Centre (KDC) - Schiphol, where access to precise historical data is made possible through collaborative initiatives with partners such as LVNL and EUROCONTROL. The Veiligheid, Efficiency en Milieu - managementinformatiesysteem (VEMMIS), an LVNL database, encompasses various critical components, including radar data, weather data, track data, and routes.
For the purposes of this research, VEMMIS serves as a valuable resource for obtaining the spawn position and conditions of historical flights that arrived at Schiphol throughout a single day in August 2019, totaling 758 flights. The selection of pre-COVID data is deliberate, as it allows for an examination of air traffic conditions unaffected by pandemic-related disruptions during that period.

5.3.5. Verification

As stated before, BlueSky is used in a lot of research and has proven to be a test worthy tool. The validations of this setup would be thus performed on Bluesky by running simulations and understanding the outcomes. It is possible to obtain actual flight data from sources like BADA and LVNL data. These can be used to draw comparisons and check for anomalies and assumptions.

5.3.6. Limitations

The simulations of the experimental can be attributed to the following reasons:

- Limitations of the simulation software (BlueSky).
- Assumptions made such as the effect of weather on CDO.
- Over simplifying the TP.
- It can be argued that the consideration of off idle descent is not the most optimum way.
- The definition of a CDO can be as strict or as lenient as required.

- Certain Data obtained from stakeholders and partners cant be published as a part of non disclosure.

the limitations of BlueSky can be attributed to the facts that:

- Its a new open source program and is under constant updates.
- The execution speed needs to be better optimized.
- Aircraft characteristics needs to be updated and the effect of aircraft characteristics on simulation is unknown.

5.4. Expected Results

5.4.1. Relationship between prediction error and the CDO success rate

Multiple simulations is to be run to determine the performance of the TPs Prediction error. A curve such that shown in Figure 5.4 would be expected where the CDO success increases with lower prediction error. Different flight levels can also be simulated for a better understanding of the TP. the curves might vary for different SD values and different distribution, but it is expected that all of the curves are expected to be similar to as shown in figure.

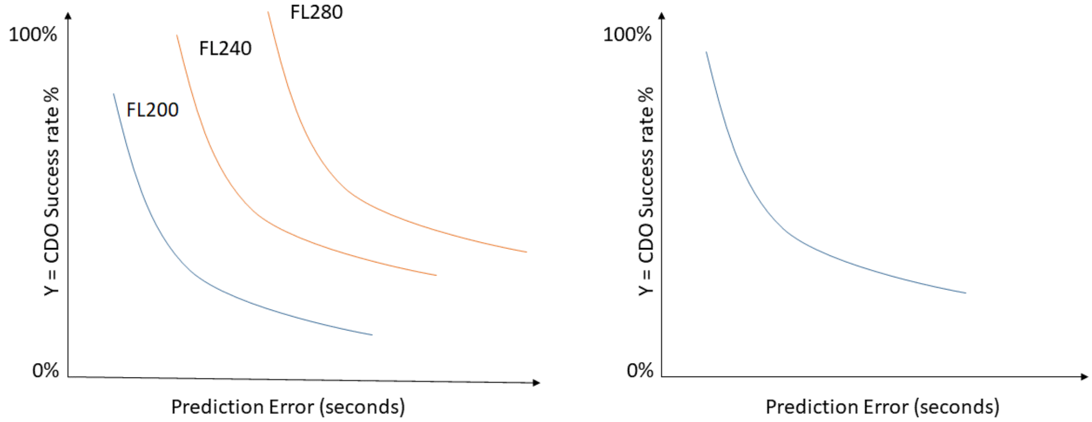

Figure 5.4: Simulation Hypothesis

5.4.2. Injecting the Air Ground Data Link Data

It can also be expected that leaner curves can be obtained with injecting noise that was processed with AGDL as compared to the ones processed without AGDL.

6 Conclusion

This report presents the literature study performed and defines the framework of the research to understand the effect of prediction accuracy on successfully implementing a CDA. The report also elaborates more on the fundamental definitions used in the research such as the definition of a CDA and the decision to select an off-idle CDA approach over an idle. It also establishes the previous research performed on CDA and highlights the benefits of flying a CDA into Amsterdam Schiphol Airport. A scientifically defined framework is then discussed which elaborates on the experiments that is to be run and the software that is used to perform these simulations.
The appendix shows the scenario files that would be used to run these simulation and a Gantt chart that highlights the research planning.

Bibliography

[1] Kars ter Beek. "High capacity Continuous Descent Operations: A case study of Amsterdam airport Schiphol". In: (2022).

[2] Bart Bouwels. "Off-Idle Continuous Descent Operations at Schiphol Airport (SARA)". In: (2021).

[3] John-Paul B Clarke et al. "Continuous descent approach: Design and flight test for Louisville international airport". In: Journal of Aircraft 41.5 (2004), pp. 1054–1066.

[4] Richard et.al. Coppenbarger. "En Route Descent Advisor". https://ntrs.nasa.gov/citations/20050009942.

[5] Paul Mark Alexander De Jong. "Continuous descent operations using energy principles". In: (2014).

[6] Jeanette Derks. "Coordinated Arrival and Departure Management". In: (2020).

[7] Joost Ellerbroek, Mazin Inaad, and Jacco Hoekstra. "Fuel and emission benefits for continuous descent approaches at Schiphol". In: 2018 International Conference on Research in Air Transportation (ICRAT2018). 2018.

[8] EUROCONTROL. U.S./Europe comparison of air traffic management-related operational performance for 2017. https://www.eurocontrol.int/publication/useurope-comparison-air-traffic-management-related-operational-performance-2017.

[9] Joost Ellerbroek Jacco Hoekstra. BlueSky Open Air Traffic Simulator. URL: https://github.com/TUDelft-CNS-ATM/bluesky/wiki. (accessed: 01.09.2016).

[10] Armand Jongen. "Concept of operations (CONOPS) Speed and Route Advisor". Internal document.

[11] TU Delft LVNL. "InnovationLabs: A joint venture between LVNL and Delft University of Technology". https://www.lvnl.nl/over-lvnl/innovationlabs.

[12] John Robinson III and Maryam Kamgarpour. "Benefits of continuous descent operations in high-density terminal airspace considering scheduling constraints". In: 10th AIAA aviation technology, integration, and operations (ATIO) conference. 2010, p. 9115.

[13] SESAR. LARGE SCALE DEMONSTRATIONS PROJECT PJ38-W3-ADSCENSIO - ADS-C Enables and Supports Improved ATM Operations. https://www.sesarju.eu/projects/ADSCENSIO.

A
Appendix

A.1. Scenario files

This is a scenario file created to feed the aircraft spawn information into BlueSky and few parameters are recorded. Additional waypoints are defined such that the arrivals fly a a specifc route which is shown later.

```
#to simulate the setsim function of tbar

00:00:00.00>DEFWPT YARMA 52.60490551344223 4.581121278305933
00:00:00.00>DEFWPT HASMI 52.59996051343656 4.683734755241533
00:00:00.00>DEFWPT WERAF 52.54822667781622 4.729400794173316
00:00:00>DEFWPT FICAH_ 52.60695348205575 4.469377497932994
00:00:00>DEFWPT UMBUB_ 52.45893840404931 4.229188779798621
00:00:00>DEFWPT EHAM_18R 52.36012053453362 4.711689073328444
00:00:00.00>DEFWPT OMEBU 52.61224523851872 4.890376355417231
00:00:00.00>DEFWPT MITJA 52.59345944830903 4.788107577371504
00:00:00.00>DEFWPT ADEVI 52.55267286755689 4.760609599793353
00:00:00>DEFWPT MORQU_ 52.59264324393692 5.296125374121468
00:00:00>DEFWPT KERCI_ 52.60972231544173 5.038940016492004
00:00:00>DEFWPT LEVKI 52.43105 4.718466667

00:00:00> crelog baseline_experiment 1 to_check_ilp
00:00:00> baseline_experiment add id lat lon alt cas gs traf.cd.inconf
00:00:00> baseline_experiment on
00:00:00> asas on
00:00:00> setsimname COMBINED
00:00:00> PERF ilp
#00:00:00> playback vemmis vemmis20190826
00:00:00> playback vemmis vemmis2019-08-0506
```

The following scenario was created to simulate arrival into runway 18C. The waypoints with their speed and altitude restrictions are as shown.

```
00:00:00.00>%0 ADDWPT MORQU_,3500
00:00:00.00>%0 AFTER MORQU_ ADDWPT KERCI_, 3500
00:00:00.00>%0 AFTER KERCI_ ADDWPT OMEBU, 2000, 220
00:00:00.00>%0 AFTER OMEBU ADDWPT MITJA, 2000
00:00:00.00>%0 AFTER MITJA ADDWPT ADEVI, 2000, 180
00:00:00.00>%0 AFTER ADEVI ADDWPT SIDNI, 2000, 180
00:00:00.00>%0 AFTER SIDNI ADDWPT AM630, 2000, 160
00:00:00.00>%0 AFTER AM630 ADDWPT TH18C, 50
00:00:00.00>%0 AT TH18C DO DEL %0
00:00:00.00>%0 LNAV ON
00:00:00.00>%0 VNAV ON
```

The following scenario was created to simulate arrival into runway 18R from the waypoint SUGOL. The waypoints with their speed and altitude restrictions are as shown.

```
00:00:00.00>%0 ADDWPT UMBUB_,3500
00:00:00.00>%0 AFTER UMBUB_ ADDWPT FICAH_, 3500, 220
00:00:00.00>%0 AFTER FICAH_ ADDWPT YARMA, 3500, 220
```

```
00:00:00.00>%0 AFTER YARMA ADDWPT HASMI, 2000
00:00:00.00>%0 AFTER HASMI ADDWPT WERAF, 2000, 180
00:00:00.00>%0 AFTER WERAF ADDWPT PEVOS
00:00:00.00>%0 AFTER PEVOS ADDWPT AM621, 2000, 160
00:00:00.00>%0 AFTER AM621 ADDWPT LEVKI, 1310, 140
00:00:00.00>%0 AFTER LEVKI ADDWPT TH18R, 50
00:00:00.00>%0 AT TH18R DO DEL %0
00:00:00.00>%0 LNAV ON
00:00:00.00>%0 VNAV ON
```

The following scenario was created to simulate arrival into runway 18R from the waypoint RIVER. The waypoints with their speed and altitude restrictions are as shown.

```
00:00:00.00>%0 ADDWPT UMBUB_,3500
00:00:00.00>%0 AFTER UMBUB_ ADDWPT FICAH_, 3500, 220
00:00:00.00>%0 AFTER FICAH_ ADDWPT YARMA, 3500, 220
00:00:00.00>%0 AFTER YARMA ADDWPT HASMI, 2000
00:00:00.00>%0 AFTER HASMI ADDWPT WERAF, 2000, 180
00:00:00.00>%0 AFTER WERAF ADDWPT PEVOS
00:00:00.00>%0 AFTER PEVOS ADDWPT AM621, 2000, 160
00:00:00.00>%0 AFTER AM621 ADDWPT LEVKI, 1310, 140
00:00:00.00>%0 AFTER LEVKI ADDWPT TH18R, 50
00:00:00.00>%0 AT TH18R DO DEL %0
00:00:00.00>%0 LNAV ON
00:00:00.00>%0 VNAV ON
```

A.2. Gantt Chart