

# **Influence of flight characteristics on the arrival process at Schiphol**

*An analysis to improve the estimated landing times*



KDC Mainport Schiphol – Centre of Excellence  
A collaboration with the Aviation Academy, Amsterdam University of Applied Sciences

Author: Bas Timmer

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<b>Author<sup>1</sup></b>		
Name	Responsibility	
Bas Timmer	Research student KDC Mainport	
Student number	E-mail	Graduation Track
500722208	Bas.Timmer2@hva.nl	Aviation Logistics

<b>Reviewers<sup>2</sup></b>	
Name	Responsibility

<b>Acceptance (by client)<sup>3</sup></b>			
Name	Responsibility	Signature	Date
	Air Traffic Control the Netherlands (LVNL)		
	KLM		
	Amsterdam Airport Schiphol		
	HvA		
	HvA Thesis Advisor		

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## **Preface**

This thesis research has been performed as a graduation assignment for the Knowledge and Development Centre. It has been developed as a follow-up on research done by the previous graduation intern.

During the graduation period, I worked with interest and pleasure on the assignment. Because of the ongoing COVID-19 pandemic most of the research had to be done from home and without the benefits of having face-to-face contact with employees at LVNL. Luckily the necessary ground work was already done before the office closed, thus limiting the negative consequences for my research. Before I started, the general concept of how the assignment was going to look like was already determined. However, the assignment had to be changed a few times during the research to better fit the needs of KDC. Unfortunately, no company supervisor was assigned to me, however with the help of Catya Zuniga and associates I was still able to gain the necessary knowledge.

First of all, I want to thank my supervisor lecturer Catya Zuniga for her guidance throughout the graduation process. Furthermore, I want to thank the KDC board for the opportunity to write my graduation thesis here. Additionally, I want to thank David Zwaaf and Ferdinand Dijkstra for their input in the later stages of the research.

Bas Timmer

Haarlem, 15 July 2020

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## List of Abbreviations

Abbreviation	Explanation
A/C	Aircraft
AAA	Amsterdam Advanced Air Traffic Control System
AAS	Amsterdam Schiphol Airport
ABI	Advanced Boundary Information
A-CDM	Airport Collaborative Decision Making
ACT	Activate message
ADEP	Departure Airport
AIBT	Actual In-Block Time
ALDT	Actual Landing Time
AMAN	Arrival manager
ASAP	Advanced Schiphol Arrival Planner
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
CFMU	Central Flight Management Unit
CISS	Central Information System Schiphol
EIBT	Estimated In-Block Time
ELDT	Estimated Landing Time
ETO	Estimated Time-over
FIR	Flight Information Region
FUM	Flight Update Message
IAF	Initial Approach Fix
IATA	International Air Transport Association
KDC	Knowledge and Development Centre
LVNL	Luchtverkeersleiding Nederland
MUAC	Maastricht Upper Area Control Centre
RWY	Runway
SSR	Secondary Surveillance Radar
STAR	Standard Arrival Route
TWR	Tower

## Summary

In a continuously growing industry, capacity problems are increasingly becoming a problem for airports all around the world. The Collaborative Decision Making (A-CDM) philosophy by Eurocontrol was introduced to improve planning reliability at Europe's busiest airports. One of the foundations of A-CDM is the sharing of data into a central data hub, displaying relevant information to all stakeholders. The Milestone Approach provides a framework in which each event is triggered by the completion of an earlier event. For some events, a time element is used to predict when the flight will arrive at this milestone. One of these time elements is the Estimated Landing Time (ELDT), predicting the Actual Landing Time (ALDT). Being able to accurately predict the ELDT is important, because it also affects the planning of the turnaround and outbound phase. To calculate an ELDT, LVNL has two systems in place: Amsterdam Advanced Air Traffic Control system (AAA), and Advanced Schiphol Arrival Planner (ASAP), with the latter being a separate module into the overarching AAA ATC system. The systems use information from data sources to calculate ELDTs. For AAA these are: ABI, ACT, FUM, and radar correlation data, and for ASAP these are: ABI, and ACT.

Previous research has been done into the frequency of reception of inbound data sources, the time window of inbound data sources, and the predictability (accuracy) of the ELDTs compared to the ALDT. During research it became clear that the predictability is undermined by outliers in the data. During this research the outliers will be analyzed two investigated if certain flight characteristics are more commonly present in the outliers. Furthermore, the above three analyses will be performed focusing on two main flight characteristics:

- **Origin:** represented by the entry sector;
- **Aircraft:** represented by the Wake Turbulence Category (WTC)

Data analysis was performed on 249.438 arriving flights during the period of the 27<sup>th</sup> of October 2018 until the 27<sup>th</sup> of October 2019. The first analysis was into the reception rate of the data sources per flight characteristic. Only 68.54% of ABI-1 is received for flights operated by *Medium (M)* category aircraft, 91.69% for *Heavy (H)* and 99.70% of *Super (J)* aircraft. When looking at the entry sectors it becomes clear that no sector has 100% receipt for ABI-messages, despite having agreements in place. *Sector 3* only sees a 4.02% receipt rate. FUM-1 is received roughly 100% across all sectors and aircraft categories. Radar correlation and ACT are received 100% due to the nature of the data. Notable is that when ABI-1 is **not** received, these flights all come from short-haul destinations with *Medium (M)* category aircraft from: Bremen, Dusseldorf, London Stansted, Humberside, and Norwich. What these airports have in common is that they are all geographically close to Schiphol. Furthermore, in *Sector 3*, where no bilateral agreement is in place, flights that do receive ABI-1 are mostly (88%) from the Air France-KLM group. For FUM-1 the opposite is true, where intercontinental flights make up most of flights that did not receive FUM-1.

The time window analysis also revealed mixed results. ABI-1 is received on average 39 minutes before arriving at the Initial Approach Fix (IAF). However, notable is that *Sector 4* flights generally receive ABI-1 five minutes later than the population. This seems to be the case for flights from airports that are located close to the London FIR border with Amsterdam FIR, with airports further east being less affected. This ties in with the fact that *Sector 5* flights (that is used more by intercontinental traffic and flights from further into the UK and Ireland) receives ABI-1 on average 2.5 minutes earlier than the population. For ACT only marginal differences could be seen when looking at the outliers. An +7% increase in *Sector 5* traffic is seen, with airports close to the Dutch border making up a relatively high percentage of flights with Brussel (+13%) and Dusseldorf (+8%) being the top ones. FUM ELDTs are generally received later for flights arriving from the west, and earlier flights from the east. Furthermore, *Heavy (H)* and *Super (J)* category aircraft receive their FUM-messages significantly earlier than *Medium (M)* category aircraft. This analysis leads to the conclusion that the geographical distance between the departure airport and Schiphol does negatively influence the moment the ABI/ACT-message is received. Intercontinental traffic from the east receives their FUM-messages earlier than continental traffic from the west.

An overarching trend could be found in the ELDT predictability analysis. Flights from sectors 4 and 5 receive less predictable and more inaccurate ELDTs. ELDTs generated from ABI-messages deviate on average only 2.5 minutes from the ALDT. However, in sectors 4 and 5

this is roughly 4.5 minutes. Compared to the less than one-minute deviation in sectors 1, 2, and 3 this is a notable difference. What sets sectors 1, 2, and 3 apart is that they see more mainland European traffic, while the others see more UK, Ireland, and intercontinental destinations. For ACT ELDTs the average deviation is two minutes, with sectors 1, 2, and 3 being the most accurate. The slightly increased distribution of *Super (J)* category aircraft is probably due to less randomness in smaller sample sizes. Notable in the ACT outliers is that an +12% increase can be seen in flights that used SUGOL as their IAF. These flights come from sectors 4 and 5. Therefore, not only are ELDTs from these sectors less accurate but they are also more unpredictable due to the outliers. Radar correlation ELDTs are the most predictable with an average deviation of roughly 1.5 minutes, and no significant differences between entry sectors and only marginal differences between aircraft categories. In the outliers, flights from Germany and UK make up a higher percentage.

For the accuracy of FUM ELDTs it is expected that with the accuracy improves with later FUM-messages. However, this is only marginally true with FUM-1 having an average of five minutes deviation, FUM-2 also five minutes, and FUM-3 four minutes. No notable differences between entry sectors and aircraft categories can be seen. In the outliers, there is a +15% increase in distribution of flights operated by *Medium (M)* category aircraft. Furthermore, these flights generally come from *Sector 4*. When filtering further, an increase can be seen in airlines: EasyJet (+3%), Flybe (+1.75%), and British Airways (+1%). What these flights all have in common is that they operate from UK airports.

The moment of arrival also seems to affect the accuracy of the ELDTs. For ABI, ACT, and radar ELDTs an increase in outliers can be seen during the busy hours of 07:00 and 10:00 UTC. This ties in with the inbound intercontinental wave from the east. For FUM, more outliers can be seen during the relatively less busy hours of 16:00 to 21:00 UTC. This all leads to the conclusion that ELDT accuracy is less when flights arrive from the London FIR. This could be due to inaccurate data sent by the London ATC, delays due to busy airspace, or more route changes creating delays.

Recommended is to investigate the low reception rate in *Sector 3* and in the meantime to use radar or ACT data to generate the ELDTs for *Sector 3* flights. Furthermore, the less reliably data in sectors 4 and 5 are also recommended to be investigated. Because currently the ELDTs do not seem to reflect the peak hours at Schiphol, an overview of the ELDT algorithm could be helpful to address this problem in the future.

## Introduction

The Knowledge and Development Centre (KDC) is a cooperation between founding members KLM, Air Traffic Control Netherlands (LVNL), and Amsterdam Schiphol Airport. It has been founded to facilitate research towards innovative solutions for a sustainable development of main port Schiphol. One of the topics that research is geared towards, is capacity management. This is an important topic because of the capacity restrictions currently in place at Schiphol Airport. Efficient use of the capacity at Schiphol, could allow the airport to grow, without the need for major infrastructural building projects. (Knowledge and Development Centre, 2020)

This thesis focusses on finding solutions to increase the predictability of the ELDTs by analysing the accuracy of the landing times estimated by two IT systems. Within the scope of the Collaborative Decision Making (CDM) philosophy, the stakeholders at the airport share data with each other to make better decisions based on data, and to make a more accurate inbound planning. During the inbound phase, the Estimated Landing Time (ELDT), generated by the LVNL systems AAA and ASAP, is an important time measurement used for many processes within the inbound phase, but is also used to trigger various other events within the turnaround phase.

To generate an ELDT, the arrival management software uses information from various data sources, such as ABI, ACT, FUM-messages, or radar correlation. When CDM was implemented, business rules were set in place to make sure that the most accurate ELDT is used to update the ELDT in the CDM portal. Figure 1 shows a simplified overview of how the generation of ELDTs is handled.

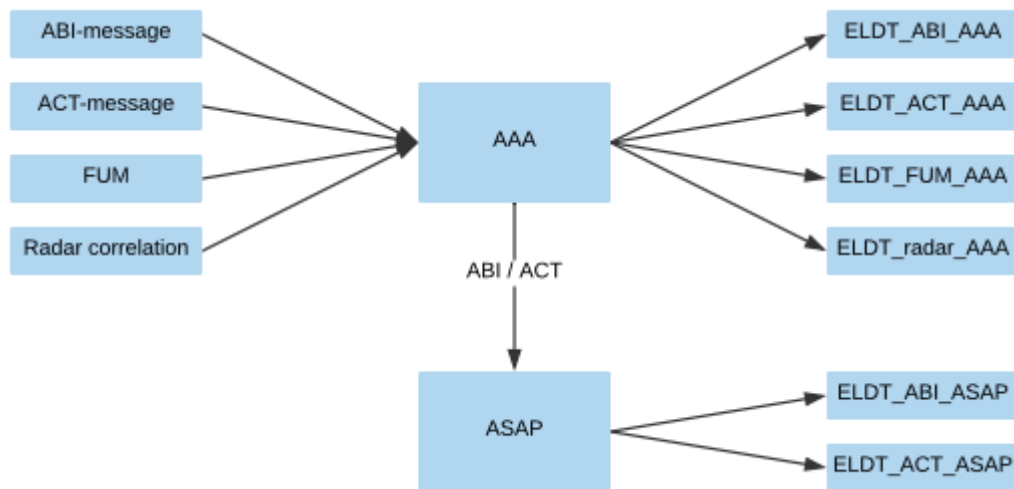


Figure 1 – Simplified overview of ELDT generation process

This thesis focusses on researching whether flight characteristics such as fleet mix have an effect on the accuracy of the ELDT, with an emphasis on why certain flights are more prone to unpredictable ELDTs.

## Problem statement

The KDC partners share data within the principles of CDM, to predict the landing times of flights. When CDM was established at Schiphol Airport, business rules were set in place to prioritize certain data sources above another. However, nowadays the quality of the data is thought to be different.

To understand what external factors play a role in the accuracy of the ELDT, an analysis is needed about the effect of flight characteristics, such as fleet mix and entry sector, on the accuracy of the ELDT. With this information, the business rules can be improved by not only taking into account the data source, but also what characteristics a flight has.

## Research Objectives

The objectives are:

- To analyse the influence of flight characteristics (fleet mix, and entry sector), on the accuracy of the ELDT, based on historical data.

## Research Questions

The main research question is formulated as:

*“Do flight characteristics (fleet mix, and entry sector) have an influence on the predictability and frequency of the Estimated Landing Time (ELDT) produced by AAA & ASAP?”*

To answer the main research question, the following sub-questions have been formulated:

1. Which are the main characteristics?
2. How do flight characteristics affect the accuracy of the ELDT and the frequency of data receipt?
3. How are the flight characteristics currently distributed in the dataset, and how do the distributions compare with the outliers?

## Research Scope

Research is focussed solely on the inbound phase of flight, until the point where the Actual Landing Time (ALDT) is submitted. Furthermore, data analysis is restricted on the data retrieved from the CDM partners, namely: ABI, ACT, FUM, Radar correlation.

The used dataset is restricted to a time span of the 1<sup>st</sup> of October 2018 until the 31<sup>st</sup> of October 2019, including one full summer and winter season.

The algorithms in the arrival management systems are not inside the scope of the research, and are considered to be a black box.

## Research Design

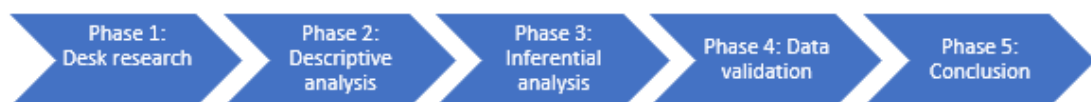


Figure 2 - Simplified process flow research design

Figure 2 shows the five general phases of research. Phase one starts with exploratory research into literature, and both internal as external documents. The second phase consists of a descriptive analysis of the flight characteristics and to explore where correlations might be present. After that, in the third phase an inferential analysis will be performed to show the relationship between the flight characteristics and the accuracy and time of receipt of the ELDTs. The fourth phase is used to validate the found data. In the last phase, conclusions are drawn.

### Phase 1: Desk Research

The first step in the research thesis is to gain the required knowledge necessary to complete the project, and to identify the knowledge gaps that might exist.



Figure 3 - Simplified process flow phase one

Figure 3 shows the topics that have been researched during the first phase. Because the research built upon the fundamentals of a previous thesis project, it was known beforehand that

for the prediction of the ELDT data sources are used. The first step was therefore, to understand the different types of data sources, and what data elements are present in the sources. Detailed documentation provided by Eurocontrol, about the OLDI-messages, and FUM's is used to gain knowledge about this subject.

The second step is to find information about the IT systems at the KDC partners that play a role in the arrival phase. The two most important systems are: AAA and ASAP. LVNL provides documentation about both systems, containing information about how the systems are linked within the IT infrastructure, and what data they use as input and what data they share.

The third step was to gain information about the implementation of CDM at Schiphol. It is known that even though Eurocontrol provides guidelines about how CDM should be implemented, it is still implemented differently at every airport. Schiphol Airport provides extensive documentation about the implemented elements and procedures of CDM at the airport. CDM documentation of Eurocontrol is used to clarify the difference between the guidelines and Schiphol's implementation.

The fourth step is to analyse the arrival phase of flight. Literature is used to gain a clear idea about how a flight goes through the arrival phase. This involves topics such as: airspace sectors (TMA, CTA, etc), CDM time elements, air routes, and approach procedures.

The last step is to obtain the necessary skills in Python to conduct a robust and correct data analysis. This was done mostly by following online courses, combined with practising with dummy data.

## Phase 2: Data analysis



The second phase of research is based on quantitative research and involves an analysis of the data. The data analysis itself is divided into three phases: a general overview of the data, time window analysis and an analysis into the accuracy of the data source. The analysis will focus on finding influence of two main flight characteristics:

- Origin of flights, represented by the entry sector
- Fleet mix, represented by the WTC

For the research a dataset containing flight information from the 27st of October 2018 until the 27st of October 2019, provided by the Capacity Management & Analytics (CM&A) department, is used. The first step is to clean the data, and delete all unnecessary variables. Appendix A, shows an overview of all variables in the dataset, that are used to do the analysis.

In the cleaned dataset, all timestamps have been converted to the Unix Epoch format. This format, counts the number of seconds that have passed since the 1<sup>st</sup> of January 1970 00:00 GMT until the corresponding timestamp. This provides a simple method to do calculations with time. When converting the string of Unix Epoch back to a readable timestamp, the time zone has been taken into account. (Raymond, 2015)

### **General overview of the dataset**

In the general overview, the dataset is explored to learn about its content. This is not only done in a general way, but also specific on flight characteristics. Information such as: number of flights per WTC, entry sector, and the distribution of WTC per entry sector are plotted. The aim of this phase is to analyse the data of arriving flights, and focussing on the two main flight characteristics, to get an overall view of the raw data and its characteristics.

### **Frequency of reception of data source information**

This phase aims to identify the reception rate for the four data sources (ABI, ACT, FUM, radar correlation), and the time window of arrival. This is done first on the whole population, and is

then divided into groups of WTCs and entry points. An analysis is made about why certain data sources are not received 100% and what flight characteristics influence this process.

The time window of receipt is the time window in which specific information from a data source can be received. This analysis takes the initial approach fix (IAF) as a reference point to calculate. First the whole population is analysed, and then groups of WTCs and entry points are made. A comparative analysis is performed to compare the behaviour of the four data sources on the time window and reception rate.

#### **Accuracy of the ELDT**

This phase aims to identify the accuracy of the ELDTs produced based on data from the four sources (ABI, ACT, FUM, radar correlation). The accuracy of an ELDT is defined as the time deviation of an ELDT compared to the actual landing time of the aircraft. This is also done on both the population and two main flight characteristics.

A more in-depth explanation about the methodology for the data analysis is found in Chapter 3.

### **Phase 3: Summarised findings**

In the third phase the findings of the analyses are summarized and conclusions are drawn. The aim is to find conclusions based on the findings in the analysis to increase stability for planning purposes. Part of this is to offer workable solutions, or recommend areas in which further research could be beneficial.

In this phase, the thesis itself is also finalized and validated by consultants.

### **Data Collection**

The data for this research project has been acquired from LVNL, and has been used in previous research into the validation of data sources. It consists of flight data, and all the generated ELDT's in the pre-planned phase. The dataset contains flight data from the 27st of October 2018 until the 27st of October 2019. Depending on the type of analysis, the data can be filtered on date. When a sample is required, the month July is used as a base. This month has been chosen because it contains the standard week that is used by KLM for their planning purposes. With KLM contributing to almost 50% of traffic, this would give a representative sample.

To gain more insight into the destinations where the flights come from, an external data source has been used. The *pyairports* Python module contains all airport IATA codes and the country the airport is in. By cross-referencing the IATA code with the ones in the dataset, the country of arrival can be added to the flight data.

# 1 Background Information

Amsterdam Schiphol Airport is the main airport of the Netherlands, and acts as a hub for KLM, Martinair, Transavia, and TUI fly. As one of the top five busiest airports in Europe, it receives flights from all continents (barring Oceania) of the world. Schiphol has an important role in ensuring the continued of the Dutch international interests, and is marked as a “main port” by the Dutch government. Because of the non-existent domestic market, Schiphol merely operates international flights, and is heavily relying on connecting passengers. Not only is it an important passenger hub in Europe, it also provides cargo services to the nation and beyond. In 2019 Schiphol served 71.1 million passengers, from 102 airlines, to 332 direct destinations. 36,1% of passengers transferred through the airport. Furthermore, 1.57 million tonnes of cargo were shipped to/from Schiphol. (Royal Schiphol Group, 2020)

Schiphol's operational capacity has been artificially limited by the Dutch government to 500.000 movements per year, up until 2020. Discussions are being held to preserve Schiphol's main port status, by relieving the airport from flights that are not contributing to the worldwide network. To counter this, Lelystad Airport is expected to open in the coming years to transfer holiday flights to, opening up extra capacity at Schiphol. Nowadays leisure and low-cost airlines make up a big part of traffic, with EasyJet and Transavia being the second largest carrier on the airport depending on the season.

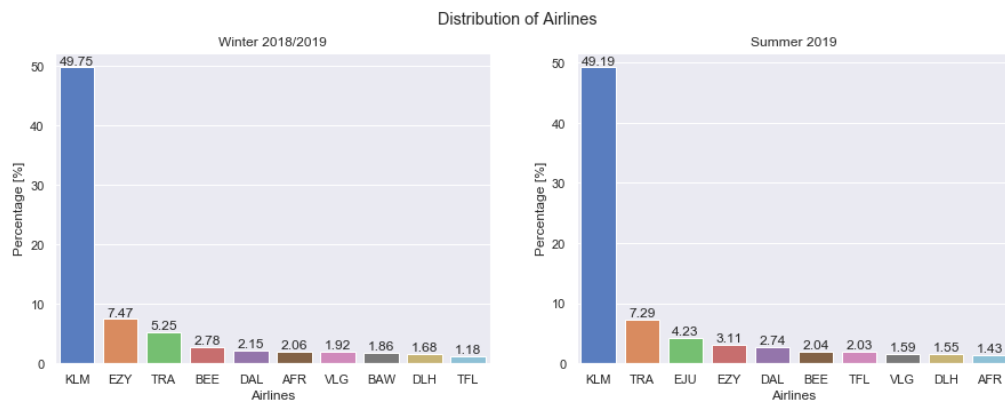


Figure 4 - Seasonally distribution of airlines at AMS

Figure 4 shows the seasonal distribution of airlines at Schiphol. It shows the extra leisure flights during the summer season, with Transavia and TUI fly taking a bigger chunk of traffic. Furthermore, Delta Airlines and Air France are well-presented into the top ten, as close KLM partners. Figure 5 shows the seasonally distribution of aircraft types at AMS. Consistent with the top ten airlines, it shows that narrow-body aircraft dominate the airport's traffic. This is partly because short-haul routes are generally operated with higher frequency than long-haul flights. With the wide-variety of airlines providing service to the airport, all modern aircraft types including the A380 are present.

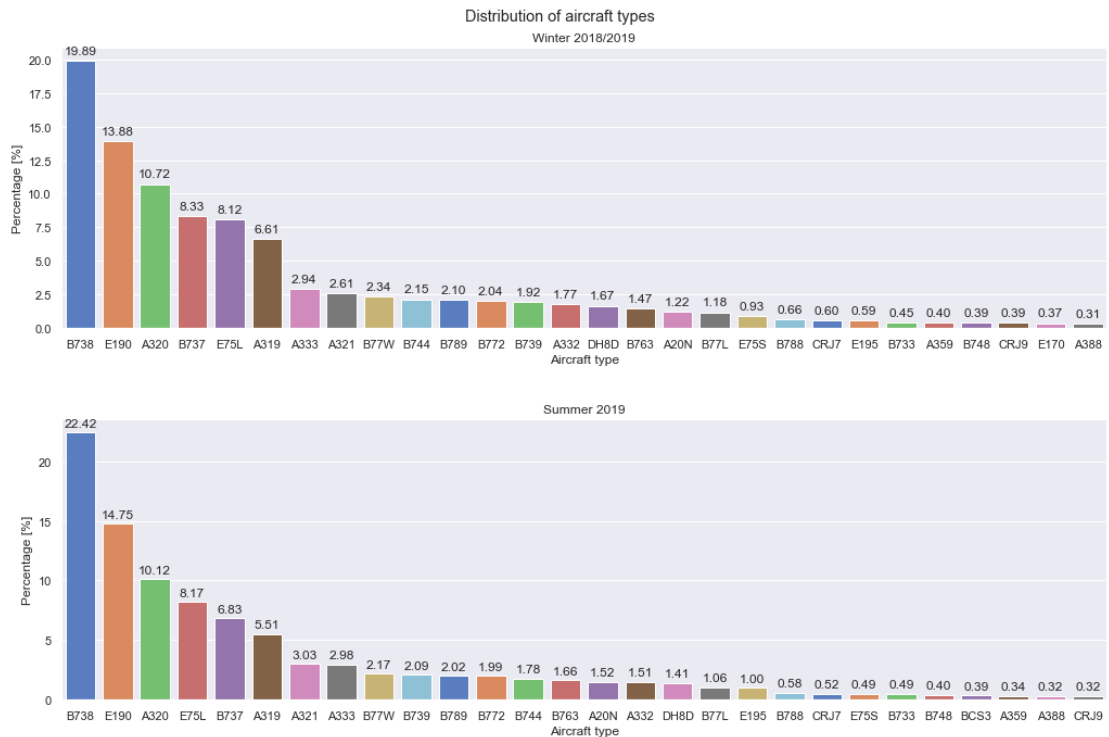


Figure 5 - Seasonally distribution of aircraft types at AMS

An airport is divided into two sections: landside and airside. Landside area is the part of the airport that is open to the public, while airside is forbidden to enter without permission, or valid boarding pass. Generally speaking, landside includes all facilities and areas prior to clearing security and/or passport control.

For the scope of this research, landside is not considered since all relevant activities are held at airside.

## 1.1 Airside

Airside is often referred to as the “sterile area”, because all passengers and personnel is security checked before entering, and have a valid reason to be there. Some airports still allow the general public to enter the airside zone for domestic flights. However, as an airport without domestic flights, this is not possible at Schiphol. Not only part of the terminal is considered airside, also the platform, taxiways, and runways are part of it.

Because research is focussed on the pre-planned phase, flights will cross different types of airspace. Airspace is defined as the portion of the atmosphere controlled by a country above its territory, including its territorial waters. As such, there are both horizontal as vertical boundaries. Nowadays the airspace is divided into various regions and controlled areas, namely FIR, TMA, and CTA.

### **Flight Information Regions (FIR)**

Eurocontrol defines a FIR as “an airspace of defined dimensions in which flight information service and alerting service are provided”. It is a three-dimensional area in which aircraft are under a single authority. A FIR can be split vertically into a lower and upper section. The upper portion of the FIR is then referred to as an Upper Information Region (UIR). (Skybrary, 2019)



Figure 6 - Amsterdam FIR boundaries (Defensie, 2018)

Figure 6 shows the Amsterdam FIR, and surrounding FIR's. Inside the Amsterdam FIR, LVNL provides ATC services to aircraft inside the FIR.

#### **Terminal Control Area (TMA)**

A TMA is a controlled area surrounding an airport, and its airspace in which air traffic services are provided. Traffic inside the TMA is generally speaking on a route to the airport, but traffic can also only cross the TMA. Besides arriving traffic, departing traffic also makes use of the TMA. The Netherlands counts eleven TMA's: (LVNL, 2020)

- Schiphol TMA 1, 2, 3, 4, and 5
- Rotterdam TMA 1, 2, and 3
- Eelde TMA
- Maastricht TMA 1, and 2 (LVNL, 2020)

Besides civilian TMA's, there are also military TMA's, namely above New-Milligen.

#### **Control Areas (CTA)**

A CTA is a controlled airspace that exists in the vicinity of an airport, which extends from a lower level to a specified upper level. It protects overflights along the ATS routes. Because Schiphol has a relatively small sized TMA, the Dutch civil CTA's also see a lot of climbing and descending traffic. In Dutch airspace, there are five entry sectors where flights can enter the Amsterdam FIR. (Ministry of Infrastructure and the Environment, 2011)

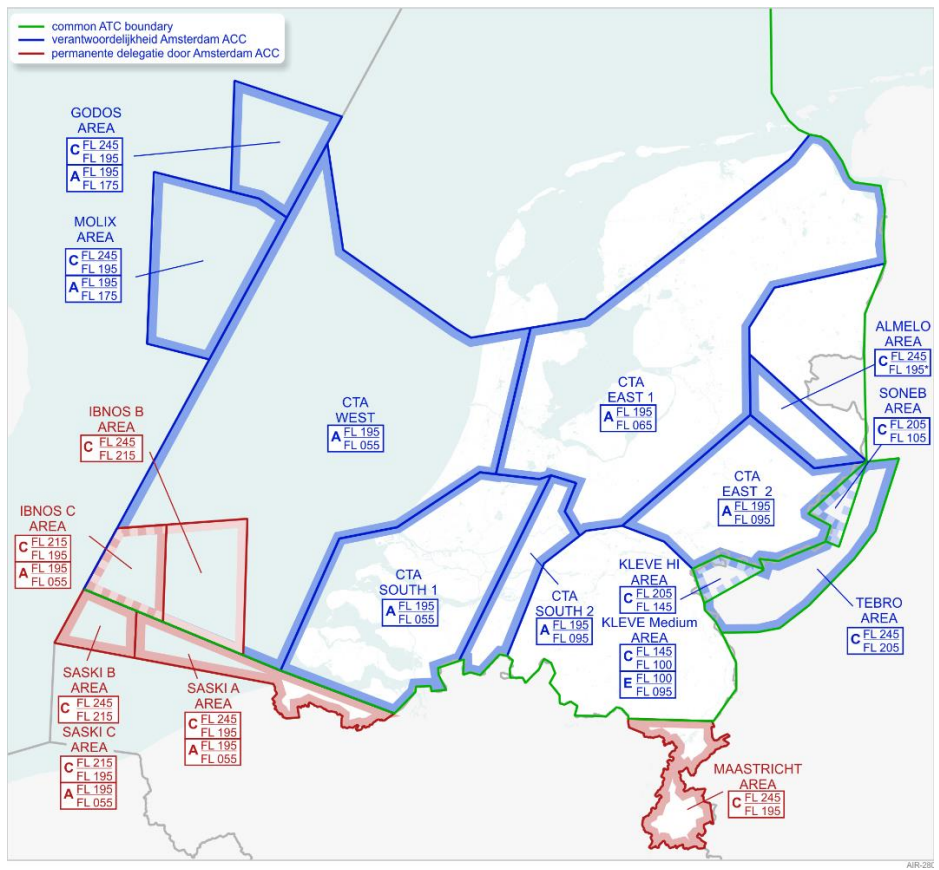


Figure 7 - Schiphol CTA sectors

Figure 7 shows the five CTA sectors in Dutch airspace. Flights enter the FIR via an entry sector based on from which ATS, or arrival route they arrive. For example, flights from southern Europe will mostly enter via Sector 3, and flights from the east via Sector 4 and 5. Because of how the ATS routes are setup through-out Europe, a flight from Paris will normally not enter the FIR via a sector other than 3.

**Arrival routes**

Because this project focusses on the inbound phase of flight, the arrival routes play a big role in the research. Arrival routes are usually Standard Instrument Arrivals (STARs), used to connect the ATS route and the beginning of the approach procedure, also known as the initial approach fix (IAF). There are three IAF's in Dutch Airspace: ARTIP near Lelystad, RIVER near Rotterdam, and SUGOL above the North Sea. Holding areas are also present near these points. (Ministry of Infrastructure and the Environment, 2011)

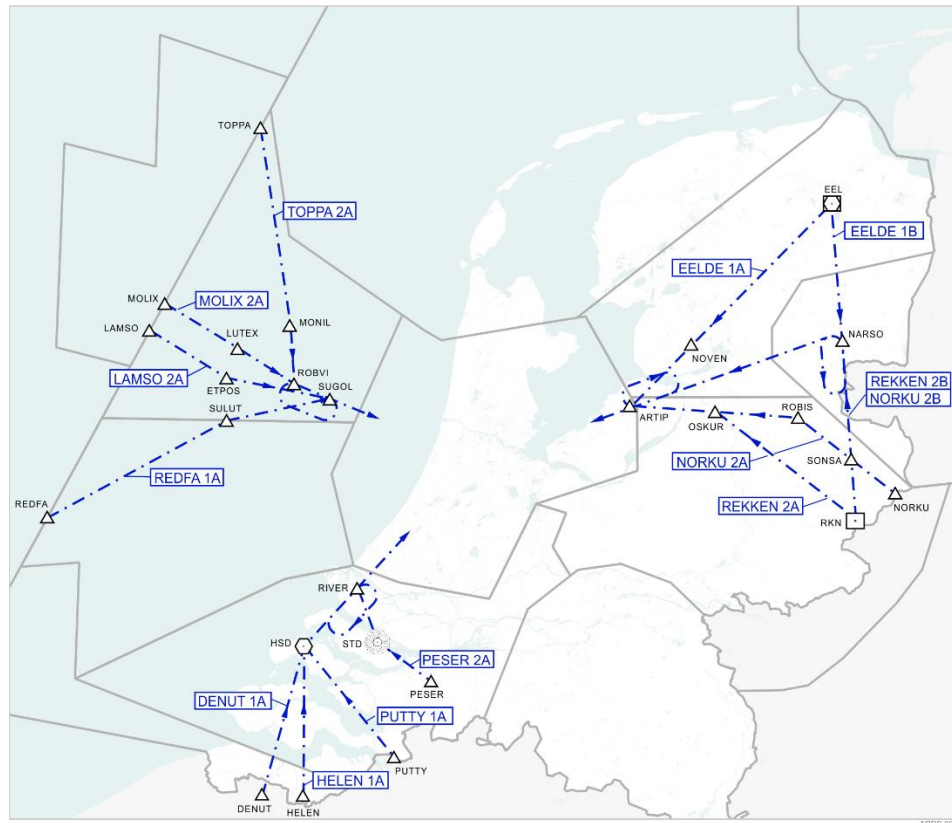


Figure 8 – Arrival routes into Schiphol

Figure 8 shows the civil route network in Dutch airspace. Notable are the holding patterns at the IAF's. The holding patterns are used to let flights hold when there is not enough capacity available at the airport.

## 1.2 Supporting IT systems in the inbound phase

Flight data during the inbound phase is collected in one central hub. However, this data is gathered from the stakeholder's own system. Multiple systems are involved in providing the stakeholders with the necessary tools to guide and prepare the flight for arrival.

### **Advanced Air Traffic Control System (AAA)**

The AAA system is the primary air traffic control system in The Netherlands. It has been specifically designed for LVNL in the 90's, but has been developed continuously in the years after. AAA consists not only of software but also hardware, to facilitate air traffic control duties in the geographical area within The Netherlands assigned to LVNL.

Besides showing flights in real time, AAA also shows information about expected flights within the Dutch airspace. To do this, it stores flights plan for flights within the next five hours in a database. The flights plan, filled by the airlines, originates from the Central Flight Management Unit (CFMU) in Brussels.

Being the main infrastructure for air traffic control, also means that other systems rely on data from AAA. The data transfer between ASAP and AAA is known as T-ASAP and F-ASAP, and the transfer between the tower TWR-AAA LINK. Any relevant information is updated in the originating system and then distributed to the linked systems. (Knowledge and Development Centre, 2013)

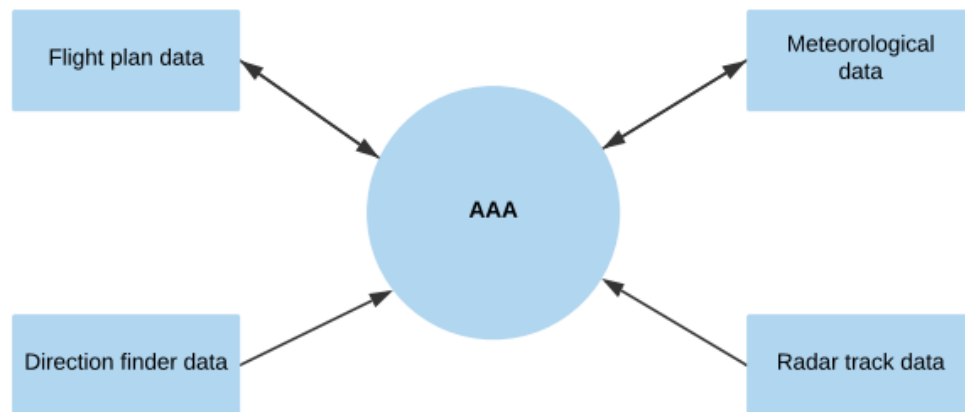


Figure 9 - Data flow diagram AAA

Figure 9 shows the data flow diagram for the AAA system. The radar track and direction finder data are only consumed by AAA, while the flight plan and meteorological data is exchanged bi-directional. Radar track data and flight plan are correlated to link tracking labels to the corresponding flights. During flight it calculates both Actual Time Over (ATO) and Estimated Time of Arrival (ETA), and sends ABI and ACT messages to the surrounding air traffic service providers. (LVNL, 2018)

#### **Advanced Schiphol Arrival Planner (ASAP)**

ASAP is an inbound planning system that has been developed to modernize the arrival planning support systems at Amsterdam Schiphol Airport. Previously the inbound planner was part of the AAA system, now with the introduction of ASAP, the inbound planner is a separate module that can be linked with AAA but also with the newly to-be-developed iCAS system that is planned to be operational in 2021. This has been done, because modernization of the current system was necessary on short term. (Knowledge and Development Centre, 2013)

The goal of ASAP is to:

1. Create stable inbound traffic flows in the Schiphol TMA.
2. Optimal use of the available runway capacity.
3. Generate accurate ELDT's.

The introduction of ASAP brings many improvements in comparison to the previous system. In contrary to AAA, with ASAP the air traffic controller can assign airspeeds earlier to a flight to prevent avoidable holdings and detours. This leads to less fuel burn for the airlines. ASAP also assigns a runway to flights, and determines the ELDT with an algorithm that takes into account: the wind direction and speed, aircraft type, and typical flight behaviour on final approach. With the Trajectory Predictor ASAP can make an accurate inbound landing planning. (Knowledge and Development Centre, n.d.)



Figure 10 - Data flow diagram ASAP

Figure 10 shows the data flow diagram of the ASAP system. The approach planner input represents the air traffic controller manually modifying the sequence planning.

### **Tower (TWR)**

The TWR system is a combined radar and flight processing system that is used by the tower, ground, and start-up controllers, and their assistants in the Schiphol tower. Its purpose is to provide the tower with track, weather, and flight plan data.

The radar data is provided by various ground and air radar sources, namely: ASTRA, MLT, SMR1, and SMR3 for ground, and ARTAS-APP, TAR1, and TARW for air. The weather data is provided by KNMI. (Grove & van Heurn, 2019)

The flight plan data comes from the AAA system, as seen in Figure 10. Besides the flight plan data, there are also towing and vehicle plans which are supplied by Schiphol Airport. It is worth noting that, in contrary to the flight plans, the towing and vehicle plans are not sent to AAA. (Grove & van Heurn, 2019)

When an aircraft is on final approach, the TWR system calculates the ELDT based on track data linked to the flight plan. After landing, the ALDT is determined and when the aircraft passes the red line at the gate, the flight is removed from the TWR and AAA systems. (Grove & van Heurn, 2019)

## **1.2.1 Sources of Information**

Essential for the workings of the systems, are the sources of information. There are many sources of information send and received to coordinate flight traffic with the various ATC units. On-Line Data Interchange (OLDI) is a protocol developed by Eurocontrol, which contains a variety of message formats, with different purposes. Besides OLDI, there are also Flight Update Message (FUM), radar correlation, and slot time.

## 1.2.2 On-Line Data Interchange (OLDI)

OLDI is a protocol introduced by Eurocontrol, to accommodate the exchange of flight data between adjacent ATC units. Its main objectives are to automate the exchange of flights data between ATC units, and to ensure timely delivery of standard messages.

The messages are formatted following common rules, that are agreed upon by the concerned agencies. The specifications for OLDI-messages are documented into Eurocontrol's "Specification for On-Line Data Interchange (OLDI)" document. (Skybrary, 2019)

The European Commission is requiring per regulation 1032/2006 that all ATC units from 2009 on, shall provide service to general air traffic, and the reliability of every OLDI link shall be at least 99,86%. (European Commission, 2006)

OLDI-messages have a few benefits, namely:

- Automation of routine actions (information exchange) which allow the controllers to focus on more complex tasks
- Reduced controller workload due to reduced need for verbal coordination
- Better situation awareness
- Indirect improvement of ATS system safety features

Three categories of OLDI-messages exist:

1. CAT1: Transfer of Communication
2. CAT2: Coordination
3. CAT3: Notification

Category one messages are mainly used to facilitate communication and negotiation between controllers in the coordination phase, and for communication in the transfer phase. Even though, these messages can also be used for flight data exchange the ACT and REV messages serve the same purpose. (Skybrary, 2019)

Category two messages are used for coordination between a civil and military airspace. The data included in the message is similar to category 3 messages, but their intention is different.

Category three messages are used for the exchange of flight data, and can be used as input for the arrival management systems. For this research, only category 3 messages are considered, because they cover all the necessary data for the AMAN's (compared to category 1), and are used by civil ATC units. (Skybrary, 2019)

Data	ABI	ACT	REV	PAC	MAC	LAM
Message type	X	X	X	X	X	X
Message Number	X	X	X	X	X	X
Aircraft Identification	X	X	X	X	X	
SSR Mode and Code	X	X	X	X		
Departure Aerodrome	X	X	X	X	X	
Estimate Data (ETO)	X	X	X	X		
Destination Aerodrome	X	X	X	X	X	
Number and Type of Aircraft	X	X		X		
Type of Flight	X	X		X		
Equipment Capability and Status	X	X	X	X		
Route *	X	X	X	X		
Other Flight Plan Data *	X	X		X		
Actual Take-Off Time *		X				
Message Reference *			X	X	X	X
Co-ordination Point					X	
Co-ordination Status and Reason *					X	
Departure Runway *				X		
SID Identifier *				X		
Cleared Flight Level *				X		

Table 1 - OLDI-message data matrix (Eurocontrol, 2017)

**Note:** data marked with \* are subjected to bilaterally agreement.

Table 1 shows a matrix with the data included in the six category three OLDI messages. It is worth noting, that some messages only contain certain data elements if they receiving and sending ATC units have an agreement to share this data.

### **Advanced Boundary Message (ABI)**

An ABI-message is an OLDI-message that notifies the next ATC unit of the flight. As such, its purpose is to: (Eurocontrol, 2017)

- Provide acquisition of missing flight plan data.
- Providing advanced boundary information and revisions for the next ATC unit.
- Updating the basic flight plan data.
- Facilitate early correlation of radar tracks.
- Facilitate accurate short-term sector load assessment.
- Requesting the assignment of an SSR code from the unit to which the above notification is sent, if required. (Eurocontrol, 2017)

Table 1 shows the data elements in the ABI-message. The route and other flight plan data elements are subjected to bilateral agreement. There are several rules of application for the ABI-message. They are as follows: (Eurocontrol, 2017)

- One or more ABI-messages shall be sent for each flight planned to cross the boundary of areas of responsibility subject to OLDI procedures.
- The use of the code request facility shall be agreed bilaterally.
- When sent, the ABI-message shall precede the ACT-message.
- ABI-message generation shall be inhibited if a PAC-message is to be sent.
- ABI transmission should be inhibited if the ACT-message is due for transmission immediately or within a bilaterally agreed time interval. (Eurocontrol, 2017)

If the next ACT-message has not been generated and any of the following elements is changed or modified, a revised ABI-message shall be sent: (Eurocontrol, 2017)

- Changeover point (COP)
- Expected SSR code at the transfer of control point.
- Aerodrome of destination.
- Type of aircraft.
- Equipment capability and status. (Eurocontrol, 2017)

If there is a change to the COP, the revised ABI-message may contain both the Estimate Data and the Route Field. Furthermore, a revised ABI-message should be sent if the subsequent ACT-message has not been generated and one of the following items is subject to change: (Eurocontrol, 2017)

- Expected boundary crossing level
- Estimated time over (ETO) at the COP differs from that in the previous ABI-message by more than the time specified in the Letter of Agreement (LoA).
- Any other data as bilaterally agreed. (Eurocontrol, 2017)

### **Activate Message (ACT)**

An ACT-message is used to replace the verbal boundary estimate by transmitting automatically details of a flight from one ATC unit to the next prior to the transfer of control. As such, its purpose is to: (Eurocontrol, 2017)

- Update the basic flight plan data in the receiving ATC unit with the most recent information.
- Facilitate distribution and display of flight plan data within the receiving ATC unit to the working positions involved.
- Enabling display of correlating in the receiving ATC unit.
- Providing transfer conditions to the receiving ATC unit. (Eurocontrol, 2017)

Table 1 shows the data elements in the ACT-message. It contains the same information as in the ABI-message, except for the addition of an Actual Take-Off Time (ATOT), if bilaterally agreed upon. (Eurocontrol, 2017)

For the ACT-message several rules of application are in place: (Eurocontrol, 2017)

- One ACT-message shall be sent for eligible flights crossing the boundary except if it is to the same co-ordination partner and it has not been abrogated with a MAC.
- The ACT-message shall be generated and transmitted automatically at the calculated time as specified in the LoA, unless manually initiated at an earlier time.
- ATC staff should be provided with the means to trigger the transmission of ACT messages prior to the calculated time of transmission.
- An ACT message shall be generated on the departure of a flight if a PAC-message, relating to the flight, containing boundary estimate data has previously been transmitted.
- The operational contents of the ACT-message due to be transmitted shall be made available at the working position responsible for the co-ordination of the flight prior to the actual transmission.
- The ACT-message shall contain the most recent information on the flight, reflecting the expected exit conditions. (Eurocontrol, 2017)

Compared to the ABI-message, the ACT-message contains the same data, with the exception of the addition of ATOT.

### 1.2.3 Flight Update Message (FUM)

The FUM is a message sent from the Enhanced Tactical Flow Management System (ETFMS) to a CDM airport by Eurocontrol. It is used to connect the airport of destination with the ATM network in order to better coordinate ATFCM with CDM airport operations, and to ensure on-time update of the flight data at the destination airport. Because the FUM is an event driven message, it can be sent as soon as the flight is airborne. This would allow the destination airport to be informed about the ELDT far ahead. When the landing time of the flight plan differs, because of a delay, LVNL will be informed of this with a FUM. (Eurocontrol, 2019)

The automatically sent FUM can contain the following main data elements:

- Estimated Landing Time (ELDT)
- Estimated Time Over (ETO) of the last point en-route or of the Inbound Approach Fix (IAF).
- ETFMS flight status (e.g. filed, delayed by ATFM, updated by CDM, etc, etc.)
- Airport type (e.g. CDM, advanced TWR)
- Status of the flight during the turnaround process, if the airport type is CDM. (Eurocontrol, 2019)

When a flight has taken off, the flight data is updated with airborne data updates from Air Navigation Service Providers (ANSP), and airlines. The updates are based on data from, for example, surveillance data updates, flight plan activation messages from ACC, and oceanic clearance messages. Some airliners send ELDT's based on ACARS messages for long haul flights. To check of erroneous messages, the update messages are validated by ETFMS and rejected if needed. The update message will then not result into a FUM. However, sometimes it is impossible for ETFMS to detect erroneous data, therefore resulting in a FUM with less accurate ELDT's and ETO's. (Eurocontrol, 2019)

### 1.2.4 Radar Correlation

Radar is an electronic system which measures the range and bearing of object by transmitting an electromagnetic pulse at an object and listening for the echo. In aviation, it has a variety of usages, mainly to track aircraft. The following types of radar are used in aviation: (Skybrary, 2017)

- Area, Surveillance, and Approach radars are used to allow controllers to track aircraft within their area of responsibility.
- Precision Approach Radars (PAR) are used to provide precision approach guidance to aircraft landing in instrument conditions. It provides an aircraft with both lateral and vertical guidance.
- Surface Movement Radar enables ground controllers to track the movement of aircraft and vehicles on an airport surface. It only provides position information, but combined with an ABS-B receiver, additional information may be displayed on the controller's screen.

- Weather Radar provides the pilot with an indication of the intensity of convective weather. Modern weather radars can detect motion of rain droplets in addition to intensity of the precipitation. Some airborne weather radar systems may also predict the presence of wind shear.
- Radio Altimeters are used to accurately measure the height of an aircraft above the surface.
- Secondary Surveillance Radar enables aircraft to pass additional information, such as identification and flight level, back to the controller. In principle, it creates two-way communication between the aircraft and radar system, in contrary to primary surveillance radar. (Skybrary, 2017)

AAA receives both primary and secondary radar tracks. By cross-referencing the SSR code from the secondary tracks with the SSR code listed on the flight plan, it can link the relevant radar tracks to that particular flight. The established correlation is then maintained during the rest of the flight. AAA can then monitor the flight, and perform calculations such as the ELDT and Actual Time Over (ATO). (Scheffers, 2020)

### 1.3 Principles of Collaborative Decision Making (CDM)

CDM is a philosophy designed by Eurocontrol, to improve efficiency and resilience of airport operations by optimising the use of resources and improving the predictability of operation. To achieve this, CDM encourages airport partners (airport operators, airlines, ground handlers, and ATC) and the network manager to work together and exchange relevant and accurate data with each other. Not only results the sharing of data in a better planning at the airport, but also within the European ATFCM network. (Eurocontrol)

Implementing CDM benefits all stakeholders on the airport. Airlines can achieve fuel savings because of better planning, reduction of delays, and increased capacity with the same fleet with tighter planning. Ground handlers benefit from having a better planning to allocate resources to. ATC can make a better pre-departure sequence based on data, and benefits from more predictable traffic overall. The airport itself benefits from having improved gate/stand planning and management and more available capacity. Furthermore, safety is also an aspect that benefits from CDM. (Eurocontrol, 2009)

Even though Eurocontrol offers guidelines on how to implement CDM, implementation is a local affair, and can be done differently because of local needs, and airport characteristics. Because CDM focusses so strongly on communication and data sharing among stakeholders, the stakeholder structure at an airport is important characteristic.

## 2 Collaborative Decision Making

This chapter describes the fundamentals of CDM and what elements have to be implemented at an airport. It starts with describing the implementation cycles (2.1) and explaining the difference between the CDM implementation guidelines and how it is actually implemented at Schiphol. After, the milestone approach with its three flight phases (2.2) is explained more in-depth.

### 2.1 Implementation cycles

CDM is implemented through the introduction of multiple operational processes. These processes can be summarized into six steps that need to be implemented.

#### Information sharing

Sharing information between stakeholders is the cornerstone of CDM. A central system has to be put in place to facilitate data sharing, before implementing any of the next cycles. At Schiphol, the existing Airport Central Information System Schiphol (CISS), has been chosen to act as the platform for the realisation of the airport CDM system. CISS gathers all flight information during the inbound, turnaround, and outbound phase of flight. However, not all information is shared with stakeholders. To determine which data source provides the best estimated time, business rules are set in place describing the source hierarchy. The source of information can be LVNL, a ground handler, or an airline system. (Schiphol Airport, 2019)

The airport's CDM system performs the following functions:

- Collect all relevant data from CDM partners.
- Calculate estimations of new events, or establish that an event has occurred.
- Make data available to all CDM partners.
- Correlate flight plan with flight in Amadeus Airport Operational Database (AODB). (Schiphol Airport, 2019)

#### Milestones approach

The milestone approach is an event driven concept that describes the progress of a flight from the initial planning to the take-off by defining milestones. This enables close monitoring of significant events, and the ability to predict forthcoming events. When a milestone is completed successfully, the decision-making processes for the next events is triggered. (Schiphol Airport, 2019)

One of the benefits of the milestone approach is the possibility to better identify potential deviations from the planning, and can trigger re-planning processes. To do this, time elements are linked to certain milestones. Schiphol has implemented the milestone approach, however, milestones three, twelve, and fourteen have not been implemented. In Chapter 2.2 the milestone approach and its implementation at Schiphol is explained further. (Schiphol Airport, 2019)

#### Variable taxi time

The variable taxi time (VTT) is the estimated time that an aircraft spends taxiing between the parking stand and the active runway, and vice versa. In contrary to a static taxi time, the variable taxi time takes into account several variables such as runway occupancy and ground movement time. This is especially important for Schiphol, because of the long taxi time to and from the Polderbaan. (Schiphol Airport, 2019)

#### Pre-departure sequence

A pre-departure sequence is the order that aircraft are planned to depart from their stands, taking into account the CDM partner's preferences. This results into a better optimisation of overall airport capacity because taxiway, and runway capacity is maximised by an algorithm instead of a first-come-first-serve base. At Schiphol, the Collaborative Pre-Departure Sequence Planning (CPDSP) module is implemented into the ATC TWR system. TSAT's, and TTOT's are provided by ATC TWR to the CDM system. (Schiphol Airport, 2019)

#### Adverse conditions

During non-normal operations, it is especially important to be able to anticipate on disruptions. Not only for the CDM partners, but also for the passengers. The CDM airport status has been

divided into four categories: normal operations (green), disruptions (yellow), severe disruptions (red), and emergency (red). At the end of each sector or capacity briefing, the CDM partners decide whether to maintain or determine the airport status. (Schiphol Airport, 2019)

### **Collaborative management of flight updates**

The collaborative management of flight updates consists of exchanging Flight Update Messages (FUM) between an CDM airport and Eurocontrol's network manager. These messages contain estimates for arriving flights, and help to improve the ATFM slot management process for departing flights. At Schiphol FUM information is used by ATC TWR to determine an ELDT for inbound flights before the flight is under active ATC control. (Schiphol Airport, 2019)

## **2.2 Milestone Approach**

As stated in Chapter 2.1 the milestone approach is an important element for implementation of CDM. Figure 11 shows the CDM milestones with their corresponding time elements. Even though there is a separation between in the three flight phases, a delay in a phase will also have an effect during later phases. For example, if a flight is delayed during the inbound phase, there is a chance it will arrive delayed causing a ripple effect in later phases. To identify possible delays during later stages, the estimated times depend on each other for calculation. A significant delay of the ELDT will most likely also trigger an update to the EIBT.

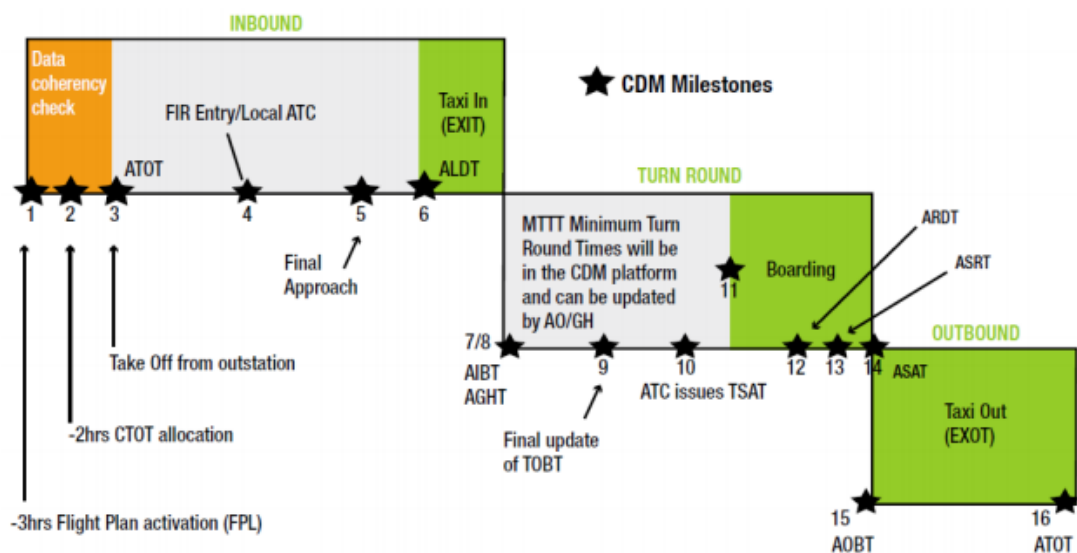


Figure 11 - CDM Milestone Approach (Eurocontrol, 2017)

### **Inbound phase**

The inbound phase is the most important phase for this research, because all analyses are performed when the flight is inside this phase. It starts with the flight plan activation three hours before the flight is supposed to arrive, and ends with the flight arriving in-block. Note that the third milestone: take-off from outstation is not implemented at Schiphol.

During the inbound phase, the ELDT is constantly updated when newer, better updates are available. Depending on where the flight is relatively to the airport, this can come from a variety of data sources: ABI, ACT, FUM, or radar correlation. Not all updates are made available in the CDM portal, but are used by LVNL. Furthermore, during the inbound phase the flight will cross different types of airspace. In chronological order these are: FIR, CTA, TMA, and then touching down on the runway, confirming the ALDT.

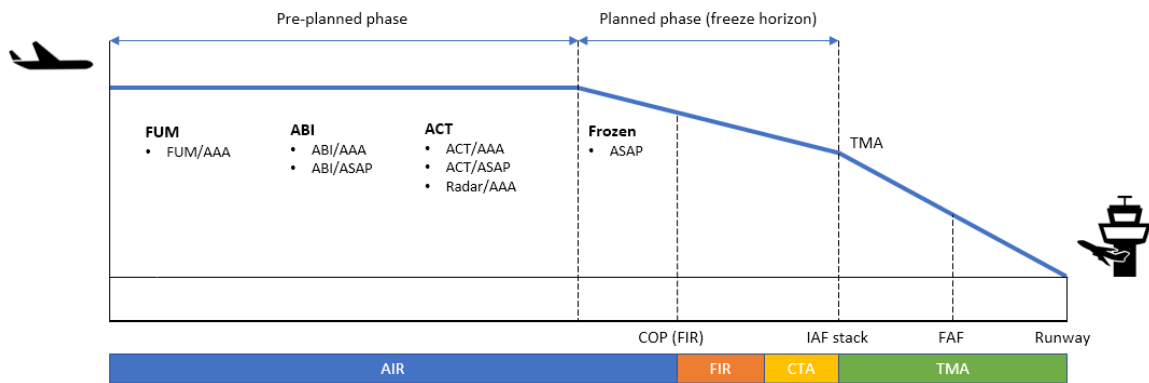


Figure 12 - Schematic overview arrival process

Figure 12 shows a schematic overview of the arrival process. The arrival process can be divided into two phases: pre-planned and planned. During the pre-planned phase, the ELDT updates are received regularly. This is done using the FUM-messages by Eurocontrol. When the first ABI-message (or ACT-message if no ABI is sent) is received, ASAP begins its calculations. When the ACT-message arrives, ELDT's are generated with radar correlation and ACT data.

When the flight is 14 minutes ETO to IAF, the planned phase begins. This is also known as the "Freeze horizon" because at this point, ASAP freezes its planning. At this point, the arrival sequence can only manually be changed by the controllers. When planning phase ends when the flight arrives at IAF, entering the TMA.

As seen in Figure 13, information from data sources is received continuously until touch down. However, only until the freeze horizon the AMAN software calculates ELDTs from these sources of information.

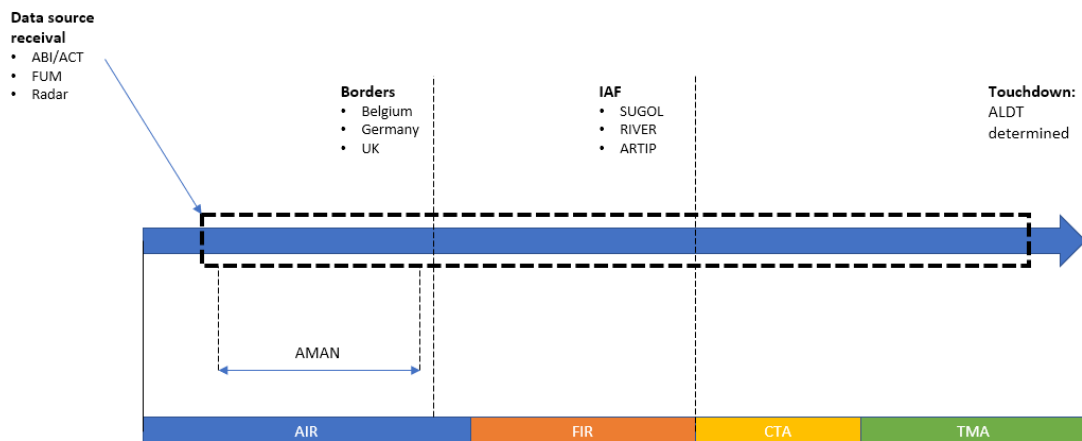


Figure 13 - Schematic overview arrival process

### Turnaround phase

The turnaround phase starts with the Actual In-Block Time (AIBT), and ends with the Actual Off-Block Time (AOBT). The duration of the phase is based on the Minimum Turn Round Time (MTTT), and the boarding time. Depending on the type of flight, the MTTT can vary from flight to flight. For example, a low-cost EasyJet flight will have a shorter MTTT than a KLM flight waiting on a transfer bank. Furthermore, the boarding duration is also dependent on the equipment used to embark/disembark the aircraft.

### Outbound phase

The outbound phase starts when the aircraft is off-block, noted by the AOBT, and ends with the aircraft taking off, marked by the Actual Take-Off Time (ATOT).

## 2.3 Pre-planned phase

This research thesis is scoped on the pre-planned phase. As stated in Chapter 2.2 during the pre-planned phase, ELDT updates for a flight are received regularly. The data for these updates can come from different data sources: FUM, ABI, ACT, and radar correlation. This data is mostly received by ATC, but the airline itself can also use its own systems to determine the ELDT. For example, ACARS, is known to be used by airlines to calculate their ELDTs.

During the pre-planned phase, the ELDT of an arriving flight is constantly updated when a new update to the time is available. When the flight has just departed, or is still far away from the destination airport, this will happen with a FUM-message issued by Eurocontrol. The ELDT in these FUM-messages is updated with a new FUM-message when new information is available to Eurocontrol. When a flight is coming closer to the airport, an ABI-message may be received. With the information from the ABI-message, the AMAN systems at Schiphol can calculate an ELDT. An ACT-message is sent when the flight is confirmed to land at Schiphol. From the moment a flight can be tracked by Dutch radar, an ELDT can also be calculated using radar correlation.

### 3 Modelling Approach

This chapter describes the in-depth methodology of the data analyses performed for the research. This also includes the methods how the data was manipulated and which Python libraries were used in the process. First, the time of receipt, and accuracy of the ELDT variables are explained (3.1), and after the methodology behind the analyses (3.2).

#### 3.1 Description of the dataset

The dataset contains flight data from 273.008 flights, during the winter season of 2018/2019 and the summer of 2019. Appendix A shows the columns in the data, with an explanation of the variable and its unit.

##### **Time window of receipt**

The time window of receipt marks the period in which an ELDT is generated from a particular data source. Figure 14 shows a schematic overview of how the time window is calculated.



Figure 14 - Schematic time window analysis

The time window is the period between the time of reception of a data source, until the time the aircraft passed the IAF. For the purpose of this research, it is assumed that the ELDT is generated without delay. To calculate the time window, two variables in the dataset are used: *Time\_source\_system* and *Time\_IAF*. The following formula can be applied on the variables to get the time window, with the x-variable representing one flight:

$$Time\ of\ receipt\ until\ IAF(x) = Time(x)_{IAF} - Time(x)_{data\ source}$$

##### **Accuracy of the ELDT**

The accuracy of the ELDT can be defined as the amount of deviation the estimated time has on the actual landing time. ELDTs in the dataset represent the estimated time the aircraft is supposed to touch down, based on a variety of data sources, generated by the AAA and ASAP systems. The sources from which there is data available are: ABI, ACT, FUM, radar correlation, and time slot. In the dataset, the columns are labelled as: *ELDT\_source\_system*. To calculate the accuracy of the ELDT, the ALDT also has to be known. The *ALDT* column in the dataset represent the time the aircraft actually touched down. The following formula can be applied to calculate the accuracy, with the x-variable representing one flight:

$$Accuracy\ ELDT(x) = ALDT(x) - ELDT(x)$$

#### 3.2 Methodology

The methodology for the data analysis can be split into three phases: general overview, frequency and reception of sources of information, and accuracy of ELDTs. This sub-chapter will go more in-depth about the used tools and libraries for the analysis.

##### 3.2.1 Phase 1: General overview of the dataset

In the first phase, visualizing the content of the dataset, and gaining knowledge about the data, is the most important goal. The aim is to characterize the overall inbound process by focussing on the two main flight characteristics: entry sector, and WTC. To do this, the *Seaborn* library is used. Seaborn is made especially for beautiful visualization, and provides a wide variety of plots. In this phase, the heatmap, donut chart, and bar plots are used to visualize the number of movements per flight characteristic.

The numbers derived from this phase, are also used in further analyses to work as a baseline to which the results can be compared to.

### 3.2.2 Phase 2: Frequency of reception of inbound information

In phase two, more data analysis is performed on specific parts. First, the reception rate of data sources is identified by dividing the number of flights that did receive a data source, with the number of flights that did *not* receive a data source. The result is the reception ratio. When *looping* through the data, information about the entry sector and WTC is added to the data frame, to also be able to identify the reception rate per WTC or entry sector. Visualization is done using the Heatmap plot inside Seaborn.

As stated in previous section, the time window is calculated by subtracting the time data information is received from the time the aircraft reached the IAF. Figure 15 shows a schematic overview of how the time window is calculated.

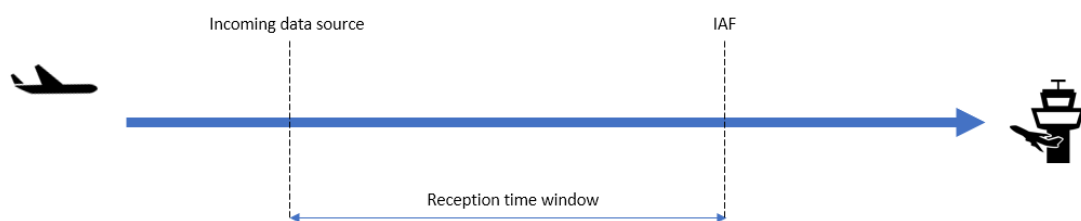


Figure 15 - Schematic overview time window analysis

The analysis is performed first on the whole population, and then divided into groups of WTCs and entry sectors. The population analysis is divided on a seasonal basis. However, when there do not seem to be significant differences between the seasons, further analyses will not be divided into summer and winter. The results are presented into a descriptive table containing the following rows: count, mean, standard deviation, min-max, median, and the percentage of outliers. An outlier is identified using the interquartile range, and calculated as follows:

- $Q1 - 1.5 * IQR$
- $Q3 + 1.5 * IQR$

For visualization purposes, a violin plot is used with an inversed x-axis to illustrate the “path” to the IAF.

After the outliers are identified, an analysis will be performed on them to see if there is a trend based on flight characteristics. This will be done mainly by comparing the distribution of characteristics with the distribution of the population.

Because of the continuous tracking by radar, this analysis cannot be performed on the radar correlation data.

### 3.2.3 Phase 3: Accuracy of ELDTs

The analysis of the ELDT accuracy is done with the same methodology as the time window analysis. A *Jointplot* with a *hexbin* structure is used to visualize the data.

## 4 General overview of the dataset

The dataset contains 249.438 flights that arrived at Schiphol during the period of the 28<sup>th</sup> of October 2018 until the 30<sup>th</sup> of March 2019. Figure 16 show the flight distribution between the two seasons. 96.532 flights arrived during winter 18/19, and 152.906 flights during summer 19.



Figure 16 - Number of arriving flights per season

From the total population, only *Heavy (H)*, *Medium (M)*, and *Super (J)* category aircraft are used in this research. Figure 17 shows the number of arriving flights for each WTC per month. In the dataset 223.125 flights were operated by *Medium (M)* category aircraft, 47.552 with *Heavy (H)* aircraft, and 869 with *Super (J)* category aircraft, which represent 82.2%, 17.5%, and 0.3% respectively. This shows that Schiphol's traffic is for a large part based on shorter routes with *Medium (M)* aircraft. Some fluctuation can be seen during the months, with dips of *Medium (M)* category flights during the winter months. The same applies for *Heavy (H)* aircraft flights, be it on a smaller scale.

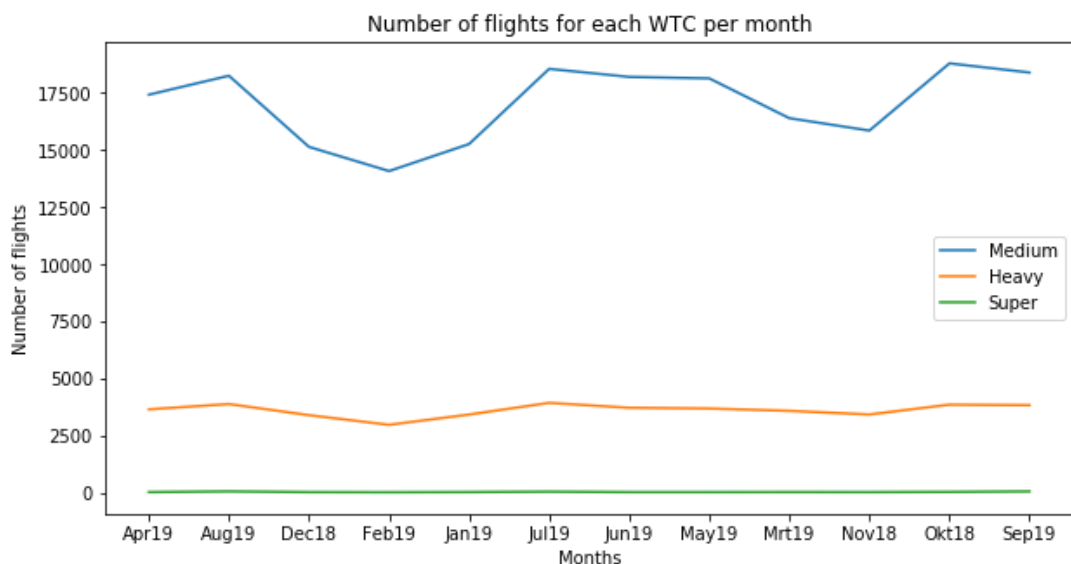


Figure 17 - Number of flights for each WTC per month

Figure 18 shows the number of flights for each entry sector per month. 42.690 flights originated from *Sector 1*, 72.025 from *Sector 2*, 72.900 from *Sector 3*, 40.988 from *Sector 4*, and 44.362 from *Sector 5*, which represent 15.6%, 26.4%, 26.7%, 15%, and 16.3% respectively. Notable is that *Sector 2* and *3* have almost 10% more traffic than the other sectors. Sectors 1, 4, and 5 have similar traffic numbers of roughly 15%.

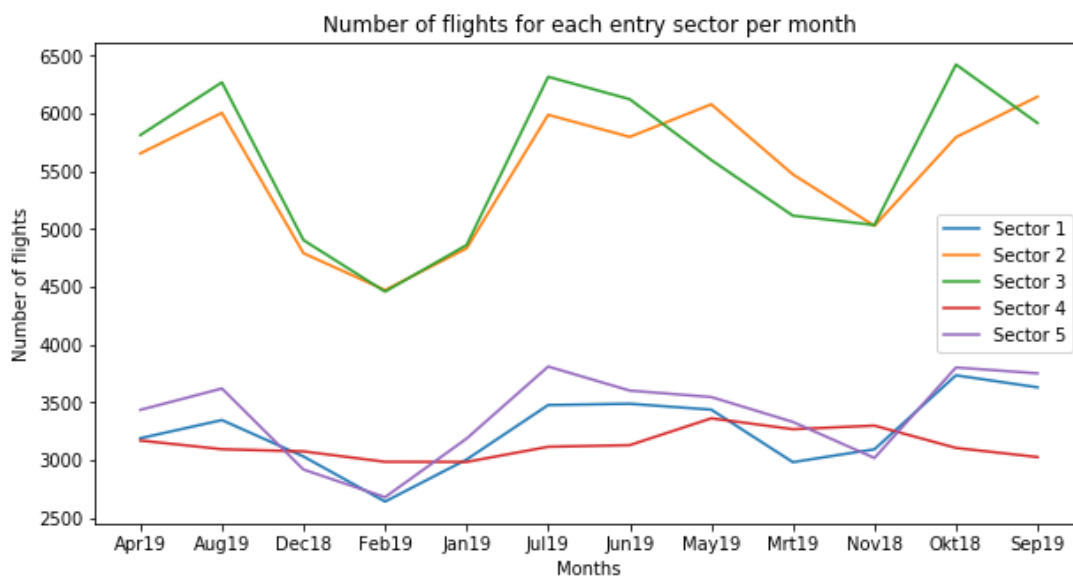


Figure 18 - Number of flights for each entry sector per month

Figure 19 shows the percentage of WTC aircraft in each sector. Sectors 1, 2, and 3 all have roughly the same distribution of WTC in each sector, with some small variation. However, in sectors 3 and 5 differences can be seen. In Sector 3, 93.77% of flights were operated by *Medium (M)* category aircraft, 5.32% by *Heavy (H)* aircraft, and zero flights by *Super (J)* aircraft. In Sector 5 more flights are operated by *Heavy (H)* aircraft compared to the other sectors. Only 64.23% of flights are operated by *Medium (M)* aircraft, and 35.60% by *Heavy (H)* aircraft. Zero flights from *Super (J)* aircraft arrived from Sector 5.

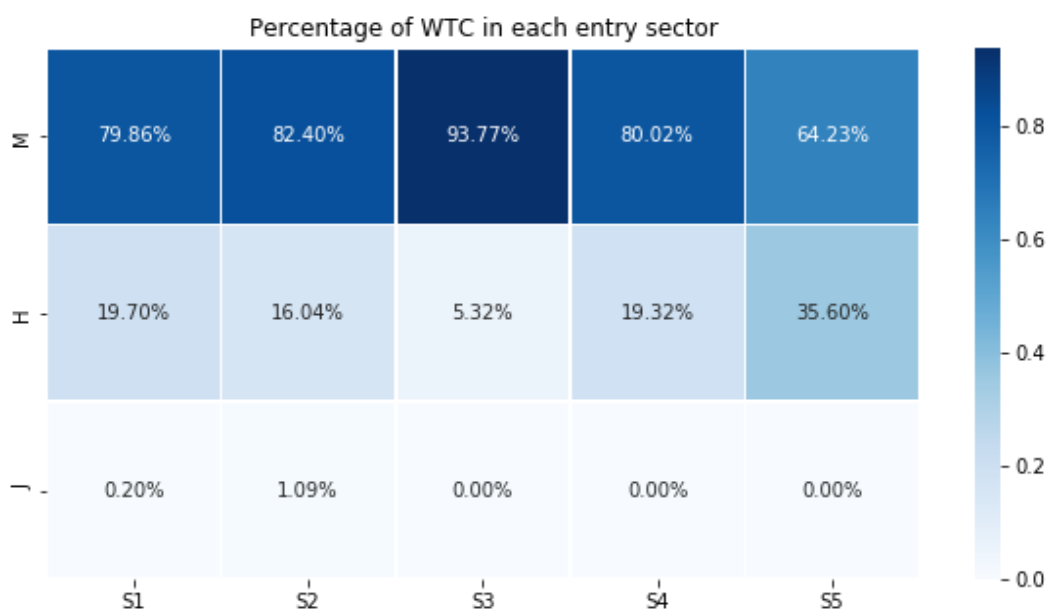


Figure 19 - Percentage of WTC in each entry sector

The origin of the aircraft plays a role in the distribution of WTC in the entry sectors. Before analysing the individual sectors, it is important to get a baseline of the region distribution in the population. Figure 20 shows the percentage of flights per region. Northern European flights make up most of the total traffic, with Southern Europe being second, and flights from the United States third.

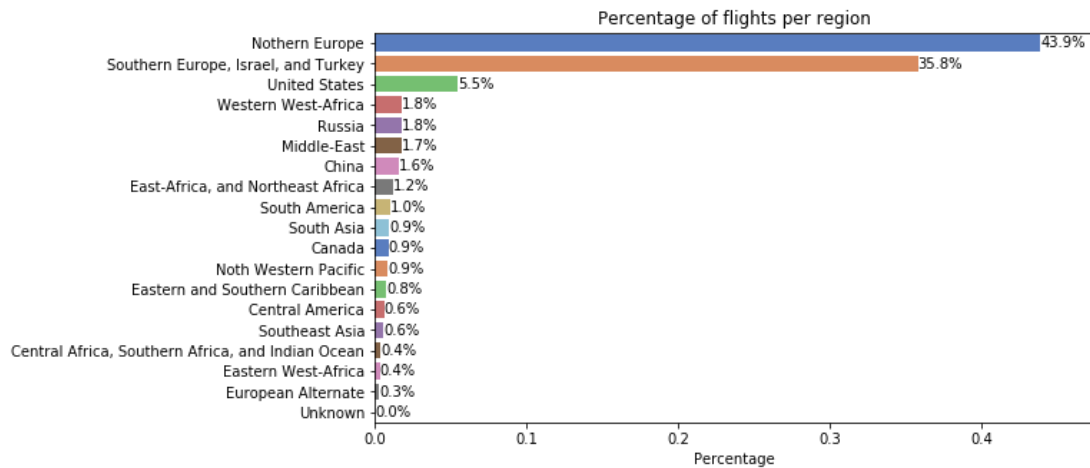


Figure 20 - Percentage of flights per region

When taken into account the origin of the flights in each entry sector, the difference in distribution becomes clear. *Sector 5's* traffic consists mostly of flights to/from European destinations flown by *Medium (M)* aircraft. A small portion of European traffic is flown by *Heavy (H)* aircraft (e.g. Amsterdam – Madrid flown with a Boeing 787 by Air Europe). This also includes fifth freedom flights. Intercontinental traffic consists here of flights to the African continent (53.6%), and South America (24%).

*Sector 4* and *5* are special because both sectors handle flights that come from the London FIR. However, there is a notable difference between the sectors. *Sector 4* sees more traffic originating from the UK and Ireland, whereas *Sector 5* sees more intercontinental traffic. This is reflected in the relative high percentage of *Heavy (H)* aircraft distribution. Transatlantic destinations in Canada (14.7%) and the United States (75.6%) make up most of traffic, but also destinations in Central America (3.8%), and Iceland. (3.2%)

## 5 Frequency of Reception of inbound information

In this chapter, the frequency of inbound information sources is analysed for the four data sources, based on the unfiltered dataset. The frequency of data source reception is the number of data messages can be received during the pre-planned phase. Besides analysing the overall reception, an analysis on reception based on the WTC and entry sector is also done to identify why some sectors or aircraft categories do not receive a data message. **(5.1)**

In the time window analysis, the amount of time that a data message is received before the aircraft arrived at the IAF point is calculated. This answer the question of how long in advance an ELDT can be generated from a data update. **(5.2)**

### 5.1 Reception of the data sources

Previous research into the frequency and reception of sources of information has found out that only a limited number of data updates can be received in the pre-planned scope.

#### **Frequency of reception of ABI-message**

Research has shown that six ABI-messages can be received during the pre-planned phase. During the summer ABI-1 is received 71.90% of times, ABI-2 1.75%, ABI-3 0.47%, ABI-4 0.10%, and ABI-1 0.01%. In the winter ABI-1 is received 73.37% of times, ABI-2 2.32%, ABI-3 0.61%, ABI-4 0.16%, ABI-5 0.06%, and ABI-6 0.02%. As seen from the numbers, the percentage of receipt is roughly the same for all six messages. (Scheffers, 2020)

As stated in the theoretical background, the ABI-messages after the first one is considered a revised ABI-message. For a revised ABI-message certain conditions have to be met: a modification to the COP, aerodrome of destinations, type of aircraft, or equipment capability and status. This all under the conditions that the next ACT-message has not been generated yet. Because of the low reception of ABI-messages after the first one, they are not considered during further analyses. (Scheffers, 2020)

#### **Frequency of reception of FUM-message**

For FUM-messages, three messages can be received during the pre-planned phase, with varying reception percentages. FUM-1 is received 99.67% of times, and FUM-2 91.47%. The third FUM-message is received 75.67% of times during summer, and 72.39% during winter. There are no significant differences in reception when comparing seasons for the first two messages. (Scheffers, 2020)

#### **Frequency of reception of ACT-message**

In contrary to the ABI-message, the ACT-message is a mandatory message. Therefore, it is received 100% of times for all flights. The same can be said for radar correlation data. Because of how radar tracks flights within its range, reception is 100%. (Scheffers, 2020)

Figure 21 shows a matrix with the breakdown of percentages of data source reception based on the WTC. Notable is that all data sources are received close to 100% for all three categories, except for ABI-1 which was received only in 68.54% of *Medium (M)* aircraft and 91.69% of time for *Heavy (H)* aircraft.

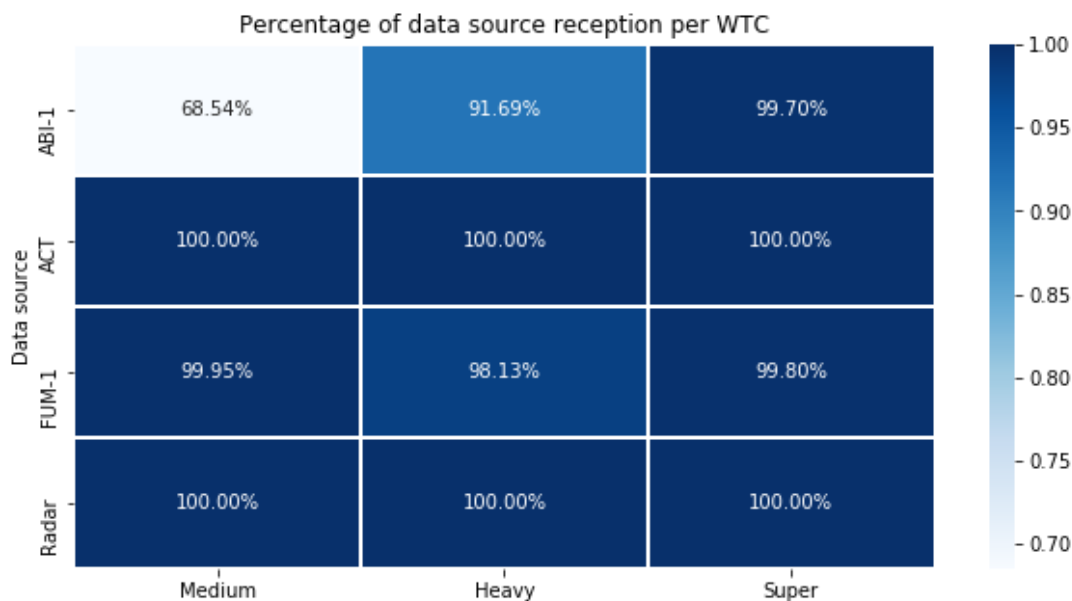


Figure 21 - Percentage of data source reception per WTC

Figure 22 shows the matrix for the breakdown per entry sector. Notable is that for all data sources except ABI-1, the data is received close to 100% of time. ABI-1 is received 96.97% in Sector 1, 94.62% in Sector 2, 4.02% in Sector 3, 99.69% in Sector 4 and 99.76% in Sector 5.

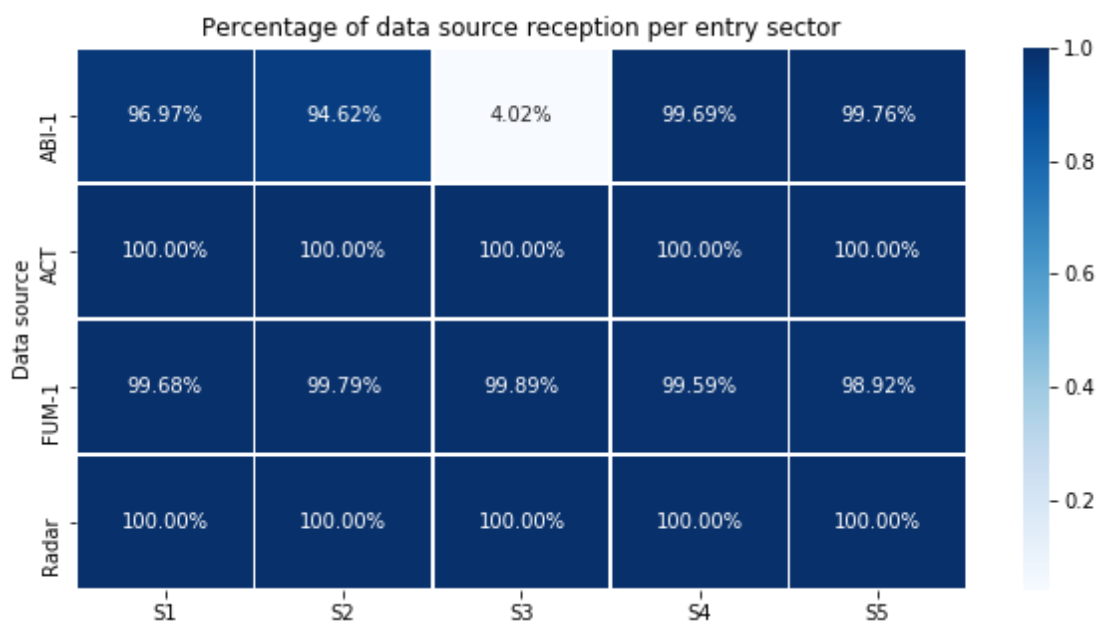


Figure 22 - Percentage of data source reception per entry sector

What is notable from previous figures is that FUM-1 is not received 100%, even though it should be. Especially *Heavy (H)* aircraft flights from *Sector 5* see a dip in FUM-1 reception. When looking at the departure airports of flights for which FUM-1 was not received, it is noted that these are mostly long-haul destinations, with a few *Medium (M)*-haul destinations. This observation is in line with the data in Figure 21 where *Heavy (H)* aircraft have a lower reception rate than *Medium (M)* aircraft.

Furthermore, from the previous figures it can be seen that there is also no 100% reception rate of ABI-1 in all sectors. Because ABI reception is dependent on bilateral agreements between ATC units, it is expected that the reception rate is either 0% or 100%. However, even though sectors 4 and 5 have roughly 100% reception, sectors 1, and 2 have not. It is known that no ABI-messages shall be sent for flights from *Sector 3*, however, the data shows that ABI-1 is received for some flights in that sector.

When looking at the destination airports it becomes clear that ABI-1 was not received for flights from six particular airports, namely: Bremen (100%), Dusseldorf (50%), Hannover (50%), London Stansted (65%), Humberside (20%), and Norwich (25%). What these six airports all have in common is that they are geographically within close to Schiphol (within 370 km).

In *Sector 3* the ABI-1 reception rate is expected to be zero. However, for some flights ABI-1 was received. Notable is that 88% of flights that did receive ABI-1 were operated by the Air France-KLM group, including Transavia. This is a +20% increase compared to the normal 68% Air France-KLM traffic distribution. Furthermore, 48% of the flights originated from Luxembourg, and 36.7% from Strasbourg.

## 5.2 Time window of receipt

The time window of receipt is the time span in which the information from the data source is received, and an ELDT is generated by the AMAN system. As a coordination point, the initial approach fix (IAF) is used. Figure 23 shows a schematic overview of how the time window of receipt is calculated.

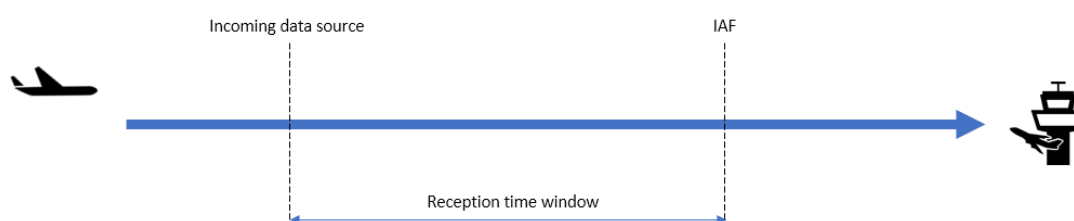


Figure 23 - Schematic time window analysis

### ABI-message

Appendix B, Figure 35 shows the boxplots of the time of receipt until IAF for the ABI-1 message, with the measures of central tendency and spread shown in Table 2. On average ABI-1 is received 39 minutes in advance, with a total time window of four hours to five minutes until IAF. With a standard deviation of  $\pm 7$  minutes it can be concluded that 99.6% of ABI-1s is received between 18 to 60 minutes until IAF.

Since the median value is roughly the same as the mean, the outliers in the data do not affect the time of receipt much. In both seasons the percentage of outliers is only 0.08%. Because there are no significant differences between the seasons, further analysis will not be divided into seasons.

	Winter	Summer
<b>Count</b>	70.815	109.917
<b>Mean</b>	00:39:04	00:39:04
<b>Standard deviation</b>	00:07:05	00:06:08
<b>Min</b>	00:15:33	00:05:51
<b>Max</b>	03:57:04	03:47:19
<b>Median</b>	00:39:28	00:39:28
<b>Outliers</b>	0.08%	0.08%

Table 2 - Time window analysis ABI-1

To identify if certain entry sectors have different time windows, the data is divided into five groups. Table 3 shows the measures of central tendency and spread for these groups. Notable is the lack of ABI-1 receipt in *Sector 3* (as explained in Chapter 5.1). The rest of the groups follow the natural distribution of the number of flights. On average ABI-1 is received 34 to 41 minutes in advance, with *Sector 4* receiving ABI-1 the latest and *Sector 5* the earliest. The total time window stays roughly the same. Compared to the population, sectors 4 and 5 stand out the most.

Notable in the outlier's percentages is the differences among the groups, with *Sector 4* as the most predictable. Sectors 1 and 2 however, have the greatest number of outliers with 0.07% and 0.08%.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	37.624	62.496	2.603	37.645	40.359
<b>Mean</b>	00:39:16	00:40:07	00:38:47	00:34:34	00:41:28
<b>Std. dev.</b>	00:04:36	00:05:10	00:20:21	00:06:47	00:05:47
<b>Min</b>	00:22:43	00:11:46	00:05:51	00:18:39	00:08:51
<b>Max</b>	03:47:06	03:57:04	03:35:31	03:47:19	03:38:46
<b>Median</b>	00:39:19	00:39:39	00:34:58	00:33:30	00:42:28
<b>Outliers</b>	0.08%	0.07%	0.03%	0.001%	0.03%

Table 3 - Time window analysis per entry sector ABI-1

When the flights are divided per WTC, some differences can also be seen. Table 4 shows the measures of central tendency and spread for these groups. ABI-1 is received on average the latest for *Medium (M)* category aircraft (38 minutes), and the earliest for *Heavy (H)* and *Super (J)* aircraft. (41 minutes). The spread of data is also much denser with a standard deviation of two to four minutes compared to the *Medium (M)* group's six minutes. This is also reflected in the number of outliers, with *Medium (M)* aircraft seeing twice as many outliers as *Heavy (H)* aircraft. The total range in the data is also much less for *Super (J)* category aircraft. However, this is probably caused by less randomness due to the significantly smaller sample size.

	Medium	Heavy	Super
<b>Count</b>	139.229	39.945	795
<b>Mean</b>	00:38:16	00:41:39	00:41:01
<b>Standard deviation</b>	00:06:33	00:03:58	00:02:18
<b>Min</b>	00:05:51	00:20:40	00:35:55
<b>Max</b>	03:57:04	03:25:34	00:55:07
<b>Median</b>	00:38:52	00:41:19	00:40:39
<b>Outliers</b>	0.04%	0.02%	0.03%

Table 4 - Time window analysis per WTC ABI-1

Compared to the population the *Medium (M)* category is the most similar. When looking at the distribution of flight characteristics some interesting observations can be seen. In the outliers from *Sector 1* and 2, most flights are arriving from German airports. Furthermore, the origin of flights arriving through *Sector 4* are mostly from UK airports (especially the London airports) that are close to the sea border. Even though flights from *Sector 5* also arrive through the London FIR, these flights mainly come from airports further into the UK, including Irish airports.

Due to poor reception of ABI-1 in *Sector 3*, it is not possible to compare it one-on-one with the other sectors.

### Conclusion ABI-message

ABI-1 is received on average 39 minutes before arriving at IAF, but can also arrive four hours in advanced and up until 5 minutes before IAF. Outliers make up 0.08% of the total flights.

When comparing on entry sectors, what is notable is that ABI-1's from *Sector 4* flights tend to arrive five minutes later compared to the total population. What sets *Sector 4* apart from *Sector 5*, which also originates in the London FIR, is that the departure airports lay close to the North Sea border. This means that the total distance between the flights origin and Schiphol is shorter. The same behaviour can be seen in *Sector 1* and 2 where flights originating from German airports tend to make up most of the outliers, while flights from airports further from Schiphol are more predictable. This leads to the conclusion that the geographical distance between the origin airport and Schiphol does affect the moment ABI-1 is received.

Even though almost no ABI-1's is received from *Sector 3* flights, it is notable that 88% of flights that do receive it are from the Air France-KLM group.

### ACT-message

Appendix B, Figure 36 shows the boxplot for the time of receipt for the ACT-message, with the measures of central tendency and spread shown in Table 5. On average the ACT-message is received  $\pm 25$  minutes before IAF, with a total time window of  $\pm 3.5$  hours. With a standard deviation of five minutes, this means that 99.6% of ACT-messages are received from 10 to 40 minutes until IAF. The total time window range is close to 3.5 hours. Outliers represent 0.02% of flights.

	Winter	Summer
<b>Count</b>	96.515	152.859
<b>Mean</b>	00:25:27	00:25:10
<b>Standard deviation</b>	00:05:37	00:05:02
<b>Min</b>	00:06:16	00:03:49
<b>Max</b>	03:46:09	03:48:48
<b>Median</b>	00:25:28	00:25:16
<b>Outliers</b>	0.02%	0.02%

Table 5 - Time window analysis ACT

When the flights are sorted into groups per entry sector, some marginal differences can be seen (Table 6). Compared to the population *Sector 3* flight receive ACT three minutes later, while sectors 1 and 2 receive it two minutes earlier. The spread in the data is a bit denser in *Sector 1* but only marginally ( $\pm 1$  minute). ACT receipt is the most predictable in *Sector 4* with the lowest number of outliers (0.03%).

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	38.820	66.038	66.303	37.756	40.452
<b>Mean</b>	00:27:38	00:27:44	00:22:31	00:23:00	00:25:39
<b>Std. dev.</b>	00:03:59	00:04:50	00:05:14	00:04:12	00:04:46
<b>Min</b>	00:08:46	00:04:15	00:05:36	00:07:31	00:03:49
<b>Max</b>	03:42:54	03:46:09	03:47:49	03:33:54	03:45:51
<b>Median</b>	00:27:18	00:27:27	00:22:15	00:22:39	00:25:13
<b>Outliers</b>	0.04%	0.07%	0.05%	0.03%	0.06%

Table 6 - Time window analysis per entry sector ACT

When dividing into WTC groups, it shows that flights operated by *Super (J)* category aircraft receive ACT the earliest on average (28.5 minutes).

Table 7 shows the measures of central tendency and spread. On average the ACT-message is received 25 minutes before IAF for *Medium (M)* and *Heavy (H)* aircraft, and three minutes earlier for *Super (J)* aircraft. Both the standard deviation and IQR, show that the data in the *Medium (M)* category is more spread, followed by the *Heavy (H)* category, with the *Super (J)* category having the least spread. Furthermore, the *Medium (M)* and *Heavy (H)* category have similar time windows of receipt at around 3 hours and 44 minutes, while the time window for the *Super (J)* category is just 24 minutes. In line with the population, the number of outliers is low for the ACT-message, ranging from only 0.01% to 0.03%.

	Medium	Heavy	Super
<b>Count</b>	203.659	43.577	798
<b>Mean</b>	00:25:06	00:25:52	00:28:38
<b>Standard deviation</b>	00:05:07	00:03:49	00:02:13
<b>Min</b>	00:03:49	00:06:39	00:17:58
<b>Max</b>	03:47:49	03:42:31	00:41:06
<b>Median</b>	00:25:10	00:25:52	00:28:19
<b>Outliers</b>	0.01%	0.01%	0.03%

Table 7 - Time window analysis per WTC ACT

When comparing the distribution in the outliers with the distribution in the population it becomes clear that *Medium (M)* category aircraft from sectors 2, 3, and 5 are more prevalent. A +7% increase in *Medium (M)* aircraft, a +5% increase for sectors 2 and 3, and a +2% increase in *Sector 5* traffic is seen.

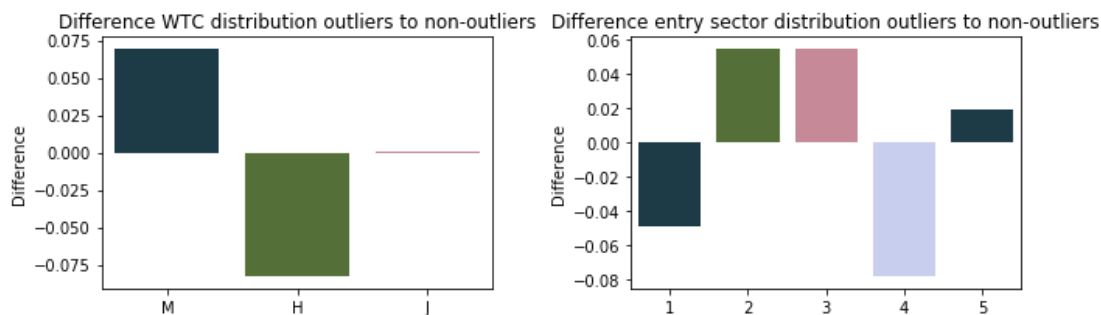


Figure 24 - Difference WTC and entry sector distribution outliers to non-outliers

From an airline aspect, differences can be seen with KLM (+11%), Air France (+2%) and Lufthansa (+1%). Airports with higher distribution than normal are: Brussel (+13%), Dusseldorf (+8%), Norwich (+6), and Paris de Gaulle (+4.2%). What these flights all have in common is that they are located relatively close to the Dutch border, especially Brussel and Dusseldorf. This leads to the conclusion that being geographically close to the border can affect the time in which ACT is send.

### FUM-messages

In contrary to the previous sources of information, the FUM-messages are received three times during the pre-planned phase, and as such there are three separate messages that need to be analysed. Appendix B, Figure 37 shows the boxplots for all three FUM-messages based on season. There are some notable differences between the three FUM-messages. The boxes for FUM-2 and FUM-3 are notably larger than for FUM-1. Furthermore, FUM-1 has a lot more outliers in its data, than the other two.

Table 8 shows the measures of central tendency and spread. On average FUM-1 is received three hours in advance, FUM-2 two hours, and FUM-3 1.5 hours before arriving at IAF. All three FUMs can be received up until IAF, with minimum values of roughly zero minutes. The maximum values can differ from six hours for FUM-1, five hours for FUM-2, and five hours until IAF for FUM-3. The standard deviation shows different levels of spread for the three messages, with 18 minutes for FUM-1, 50 minutes for FUM-2, and 48 minutes for FUM-3. This means that the FUM-1 data is denser than the larger spread seen in FUM-2, and FUM-3.

The time window in which the FUM-messages can be received also varies a lot, because during the summer season there are no outliers that can skew the range towards a particular point. Furthermore, FUM-2 and FUM-3 can also be received after the IAF reference point. This is, however, not reflected in the table or plot.

	FUM-1		FUM-2		FUM-3	
	Winter	Summer	Winter	Summer	Winter	Summer
<b>Count</b>	96.164	152.166	87.487	138.413	68.347	113.770
<b>Mean</b>	02:56:08	03:00:42	01:54:32	02:09:06	01:32:05	01:42:51
<b>Std. dev.</b>	00:18:54	00:18:11	00:51:30	00:49:29	00:48:29	00:48:54
<b>Min</b>	00:00:04	00:00:01	00:00:00	00:00:00	00:00:00	00:00:01
<b>Max</b>	06:15:49	03:52:01	05:03:07	03:50:43	04:57:31	03:48:04
<b>Median</b>	02:53:33	02:58:16	01:57:10	02:21:10	01:24:33	01:39:31
<b>Outliers</b>	0.06%	0.03%	0%	0%	0%	0%

Table 8 - Time window analysis FUM

Appendix C, Table 24 shows the measures of central tendency and spread for FUM-1, with flights dividing into entry sector groups. On average FUM-1 is received two hours and 54 minutes before IAF in sectors 3, 4, and 5. In Sector 1, and 2 the average is around two hours and 59 minutes. Notable is that outliers in the data are located mostly on the right side, meaning FUM-1 is sometimes received much later than usual. The standard deviation is consistent across the board, falling in line with the population's 18 minutes.

In Appendix C, Table 25 shows the measures of central tendency and spread for FUM-2, with entry sector groups. Notable is the difference in average time of receipt between sectors 1-2-

3, and 4-5. FUM-2 is received on average  $\pm 30$  minutes later in sectors 4 and 5, especially during the winter. Furthermore, the data is more spread in these sectors compared to the other three and the population.

In Appendix B, Table 26 shows the descriptive statistics for FUM-3. Notable is the difference between seasons, with flights during the winter receiving FUM-3 almost 20 minutes later. Compared to the population, sectors 4, and 5 receive FUM-3 almost 20 minutes later. Because the median values differ sometimes more than 15 minutes, it can be concluded that outliers do affect the overall statistics.

Dividing the flights into WTC groups, some notable differences can be seen. Table 9 shows that on average *Medium (M)* category aircraft receive FUM-1 the latest, followed by *Heavy (H)* and *Super (J)* aircraft. Furthermore, the spread of data for *Heavy (H)* aircraft is almost four minutes higher compared to the other two categories and population. The maximum time FUM-1 can be received is also  $\pm 2.5$  hours later for *Medium (M)* aircraft. Most outliers can be found in the *Medium (M)* category.

	Winter			Summer		
	Medium	Heavy	Super	Medium	Heavy	Super
<b>Count</b>	78.357	16.981	304	125.202	25.658	491
<b>Mean</b>	02:54:26	03:03:51	03:17:48	02:59:54	03:04:38	03:12:50
<b>Std. dev.</b>	00:17:48	00:21:05	00:17:19	00:17:21	00:21:01	00:13:21
<b>Min</b>	00:01:10	00:00:04	00:00:52	00:02:33	00:00:01	03:06:26
<b>Max</b>	06:15:49	03:51:06	03:47:37	03:52:01	03:51:30	03:44:49
<b>Median</b>	02:51:45	03:01:34	03:18:19	02:57:24	03:02:25	03:12:25
<b>Outliers</b>	0.07%	0.02%	0.01%	0.04%	0.02%	0.04%

Table 9 - Time window analysis per WTC FUM-1

Table 10 shows the same groups but for FUM-2. The same behaviour can be seen with *Super (J)* flights receiving FUM-2 almost two hours and 40 minutes in advance, while it is “only” close to two hours for *Medium (M)* and *Heavy (H)* aircraft. The spread in the data is also much larger for *Medium (M)* and *Heavy (H)* than for *Super (J)* aircraft which is more concentrated. When comparing to the population, the *Super (J)* category stands out while the *Medium (M)* and *Heavy (H)* groups fall more in line.

	Winter			Summer		
	Medium	Heavy	Super	Medium	Heavy	Super
<b>Count</b>	77.001	9.685	283	123.638	13.545	416
<b>Mean</b>	01:53:46	01:59:51	02:40:38	02:09:56	02:01:09	02:32:01
<b>Std. dev.</b>	00:49:38	01:04:07	00:23:23	00:47:26	01:04:54	00:37:45
<b>Min</b>	00:00:06	00:00:00	00:01:43	00:00:03	00:00:00	00:00:19
<b>Max</b>	05:03:07	03:45:52	03:12:36	03:50:43	03:48:43	03:32:13
<b>Median</b>	01:54:58	02:21:43	02:44:25	02:20:39	02:30:43	02:43:07
<b>Outliers</b>	0%	0%	0.05%	0%	0%	0.19%

Table 10 - Time window analysis per WTC FUM-2

Table 11 shows the groups for FUM-3. In contrary to FUM-2, *Super (J)* aircraft receive FUM-3 relatively late compared to the other groups and the population. Furthermore, the spread in the data is more comparable with the other groups. However, more spread can be seen in the *Heavy (H)* group. Notable differences can be seen between the seasons, with earlier receipt during the summer.

	Winter			Summer		
	Medium	Heavy	Super	Medium	Heavy	Super
<b>Count</b>	64.217	3.583	82	107.729	5.158	127
<b>Mean</b>	01:32:23	01:28:29	00:51:35	01:43:11	01:37:05	01:12:21
<b>Std. dev.</b>	00:47:40	01:00:51	00:47:17	00:48:18	00:59:36	00:56:03
<b>Min</b>	00:00:00	00:00:03	00:00:27	00:00:01	00:00:01	00:00:58
<b>Max</b>	04:57:31	03:39:45	02:44:22	03:48:04	03:40:18	03:22:46
<b>Median</b>	01:24:39	01:23:22	00:40:47	01:39:12	01:50:52	00:48:43
<b>Outliers</b>	0%	0%	0.13%	0%	0%	0%

Table 11 - Time window analysis per WTC FUM-3

When analysing the outliers, no notable differences (<1%) in distribution can be found for the outliers in FUM-1. However, for FUM-1 there is a small increase of +1.3% in distribution of *Heavy (H)* aircraft, accompanied by an increase of +30% and +13% in sectors 3 and 2. Looking at the distribution of airports, most increases can be seen in Antalya (+11%), Paphos (+6%), Tenerife Sur (+6%), Gran Canaria (+6%), and Alicante (+5%). Except for Alicante, these are all *Medium (M)*-haul destinations that see (partially) widebody traffic. It can therefore be concluded that FUM-2 outliers are most often *Medium (M)*-haul flights with *Heavy (H)* category aircraft.

For FUM-3 outliers, a small increase in *Medium (M)* aircraft can be seen (+1.5%) from sectors 1 (+1.5%), 2 (+3%) and 3 (+4.2%). Further analysis shows that there is an increase of +4% in flights coming from both ARTIP as RIVER IAF. The departure airport distribution shows an equal increase in all airports from these sectors, without one particular outlier. This leads to the conclusion that flights from these sectors have more unpredictable FUM-3 arrival times, with the cause being Eurocontrol.

#### **Radar correlation**

Due to the continuous nature of the reception of radar correlation data, the same analysis cannot be performed on the radar correlation data.

#### **Conclusion time window analysis**

Figure 25 shows the combined time of arrivals for all data sources. When looking at the plot, it can be seen that the FUM-messages can be used to calculate an ELDT the earliest, followed by ABI-1, and ACT. Even though, the first FUM-1 should come in first, there is no specific time in which it is received. This can be seen due to the fact that in some cases FUM-2 is received for a flight, while for another flight FUM-1 has not been received yet. Furthermore, outliers in ABI and ACT data show that in some occasions ABI-1 can be received around the same time FUM-1 is received. This seems particularly true for *Medium (M)* aircrafts, with a relative high amount of spread out outliers.

For the FUM-messages, there is a difference between winter and summer. During the winter season, the time of arrival is later than during the summer. In general, FUM's are received later for flights from Sector 4 and 5. The receptions of further FUM-messages after FUM-1 is especially less for *Heavy (H)* and *Super (J)* aircraft. While *Super (J)* aircraft still receive FUM-2 often, there is a big dip in arrival for FUM-3. *Medium (M)* aircraft do receive FUM-2 and FUM-3 relatively often.

Because arrival overlaps different types of data, the moment FUM-1 is received until IAF is covered. This would mean that there is almost no "gap" between reception of data sources, and thus reliable ELDTs can be generated.

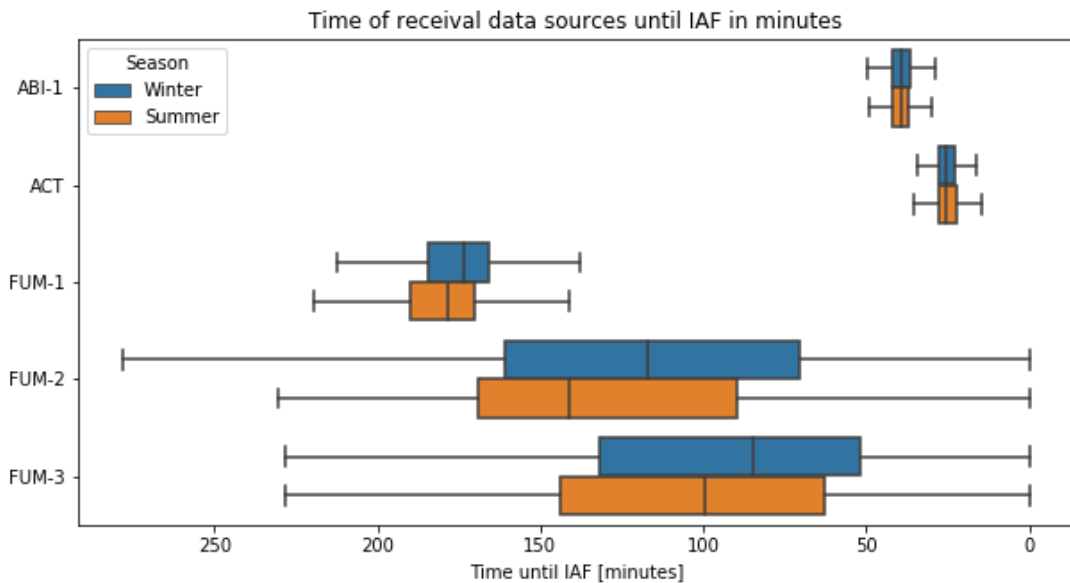


Figure 25 - Combined data source time of reception

Based on the outlier analysis, different behaviour can be seen across the three FUM-messages. With FUM-1 no notable differences in flight characteristics distribution could be seen that would justify the outliers. In FUM-2 big increases in *Sector 2* (+13%) and 3 (+30%) can be seen with *Heavy (H)* aircraft in particular. These flights mostly come from *Medium (M)*-haul destinations as Antalya (+11%), Paphos (+6%), Tenerife Sur (+6%), and Gran Canaria (+6%). FUM-3 then sees a totally different behaviour than FUM-2, with a small increase in *Medium (M)* sized aircraft instead of *Heavy (H)* ones.

The inconsistencies in behaviour of the FUM-messages reception can be attributed to the fact that FUM-messages, in contrary to the other data sources, does not have a specific time or location when it should be sent. Eurocontrol only sends it when an event happens. This leads to the conclusion that the forming of outliers can't be explained alone by specific flight characteristics.

## 6 Accuracy of the estimated landing times

This chapter contains the analysis of the accuracy of the ELDTs generated with data from ABI, ACT, FUM, and radar correlation. The accuracy of an ELDT is defined as the deviation from the ALDT.

### ABI-message

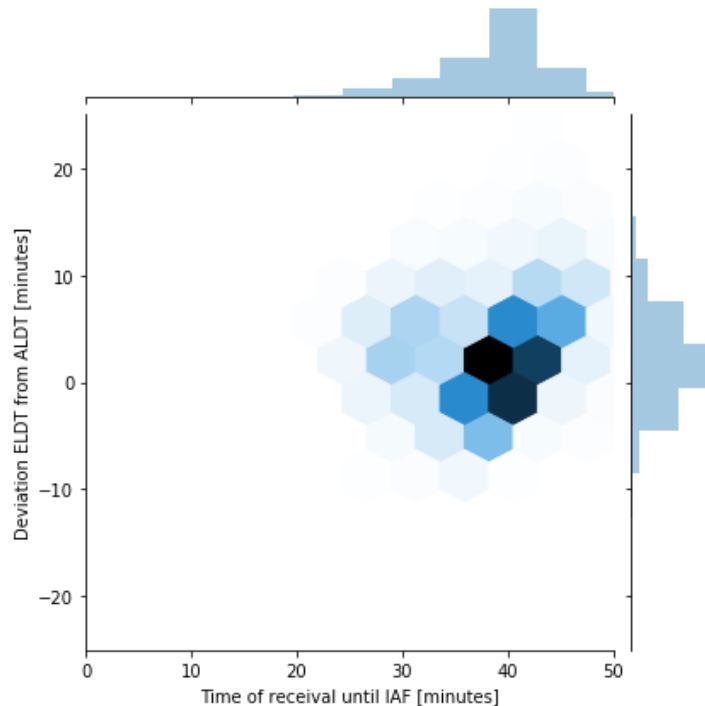


Figure 26 - Time of receipt against accuracy of ELDT ABI-1

Figure 26 shows the hexagonal binning plot with the ELDT accuracy against the time of receipt of the data. It shows the compact area in which the data is concentrated. Looking at the plot, it shows that the accuracy follows a normal distribution. The time of receipt however shows a distribution that is skewed to the left. Most data is located around the 40 minutes mark.

Table 12 shows the measures of central tendency and spread for the accuracy of ABI-1 ELDT's. On average the ELDT deviates 2,5 minutes from the ALDT. However, it is also possible for it to be more than two hours off. Given the standard deviation of roughly five minutes, it can be concluded that 99.6% of ELDT's deviate between -13 and 17 minutes from the ALDT. Because the median value of two minutes is less than half a minute of the mean it also shows that the outliers do not influence the average accuracy much. The natural difference in the number of flights per season is also reflected in the count row. Outliers in the data represent about 3% of flights.

Because no significant differences can be seen between the seasons, the next analyses will not be divided into winter and summer.

	Winter	Summer
<b>Count</b>	70.825	109.937
<b>Mean</b>	00:02:28	00:02:21
<b>Standard deviation</b>	00:05:00	00:04:37
<b>Min</b>	-01:16:59	-01:11:25
<b>Max</b>	01:50:46	02:04:16
<b>Median</b>	00:02:06	00:01:52
<b>Outliers</b>	2.88%	3.08%

Table 12 - Accuracy analysis ABI-1

When dividing the data into groups of flights per entry sector, differences in accuracy between flights from different entry sectors can be spotted. Table 13 show the measures of central tendency and spread between the entry sectors.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	37.790	62.331	2.627	37.448	40.541
<b>Mean</b>	00:00:44	00:01:06	00:00:25	00:04:31	00:04:05
<b>Std. dev.</b>	00:04:17	00:04:34	00:07:00	00:04:35	00:04:34
<b>Min</b>	-01:17:00	-01:11:25	-00:43:18	-00:24:36	-00:58:29
<b>Max</b>	01:25:37	02:04:16	01:32:30	01:19:25	01:39:15
<b>Median</b>	00:00:22	00:00:45	00:00:23	00:04:04	00:03:37
<b>Outliers</b>	3.66%	3.65%	0.14%	3.44%	3.67%

Table 13 - Accuracy analysis per entry sector ABI-1

Notable are the differences in accuracy between the groups. ELDT's from *Sector 1, 2, and 3* deviates on average only roughly one minute, while *Sector 4 and 5* ELDT's are off by  $\pm 4$  minutes. The range in *Sector 1, and 2* are, however, larger than for sectors 4 and 4. The spread in the data is roughly the same (4,5 minutes) for all sectors except *Sector 3*. Only minor differences can be seen in the number of outliers in the groups, except for *Sector 3*. Around 3.5% of ELDT's in the groups are considered an outlier. Because of the low sample size in *Sector 3*, less randomness is expected.

Compared to the population, the average accuracy of *Sector 1, 2, and 3* is almost two minutes better. ELDT's in *Sector 4 and 5* are two minutes worse than the population. The same behaviour can be seen for the median value. What sets sectors 1, 2, and 3 apart from sectors 4, and 5 is that they see more mainland European traffic, while the latter sees mostly flights from the UK, Ireland, and intercontinental destinations. In Chapter 4 it is stated that especially in *Sector 5* the number of *Heavy (H)* category aircraft, and thus more intercontinental traffic, is higher than the other sectors. Table 14 shows the measures of central tendency and spread for the groups divided per WTC. It shows that *Medium (M)* and *Super (J)* category aircraft on average have less deviation ( $\pm 1$  minute) from the ALDT. Furthermore, the *Medium (M)* and *Super (J)* category are more predictable because less outliers are present in the data. The range of accuracy is the same for both *Medium (M)* and *Heavy (H)* aircraft. The ELDT accuracy for *Super (J)* aircraft is a lot less compared to the other groups, but this can be attributed to less randomness in the data because of the substantially smaller sample size.

	Medium	Heavy	Super
<b>Count</b>	139.184	40.030	803
<b>Mean</b>	00:02:13	00:03:02	00:02:49
<b>Standard deviation</b>	00:04:54	00:04:32	00:04:07
<b>Min</b>	-01:16:59	-01:09:31	-00:07:41
<b>Max</b>	02:04:16	01:50:01	00:36:31
<b>Median</b>	00:01:46	00:02:28	00:02:30
<b>Outliers</b>	2.76%	3.80%	2.49%

Table 14 - Accuracy analysis per WTC ABI-1

As seen in the tables, outliers exist in the data. Important to know is that an outlier can exist because of two reasons: the ELDT did not represent a valid estimation of the landing time, or the aircraft encountered a delay after the ELDT was generated. When comparing the outliers against the population, no significant difference could be found. However, when looking at the moment of arrival some interesting statistics can be seen.

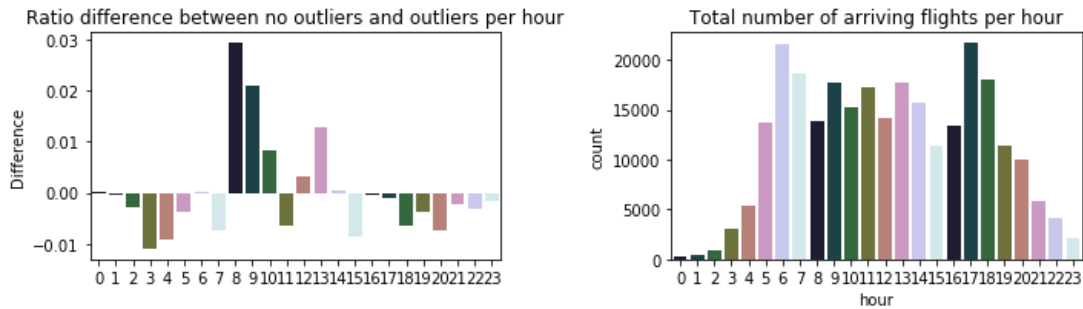


Figure 27 - Difference in ratio between outliers and no outliers

Figure 27 shows the differences in ratio between non-outliers and outliers. From the plot it can be seen that during the hours of 8 until 10, and 12 until 13 UTC, peaks can be seen where most outlier flights arrive. Even though there are not necessarily peaks during these times in total movements, the outlier peaks can only be seen during Schiphol’s busy hours in the morning.

**Conclusion ABI-message**

The ABI-1 message provides the CDM partners with an accurate ELDT. On average the difference between the ELDT and ALDT is only  $\pm 2.5$  minutes. With 99.6% of the ELDTs deviation between -13 and 17 minutes, the landing times are relatively predictable.

When comparing the deviation between entry sector groups it becomes clear that flights from Sector 1, 2, and 3 have more accurate landing times, than flights from Sector 3, and 4. This can be attributed to the fact that Sector 4, and 5 see more flights from non-mainland Europe and intercontinental destinations. Landing times from Heavy (H) category aircraft are off by one minute on average compared to the Medium (M) and Super (J) category. Furthermore, Heavy (H) aircraft have more outliers and the landing times are therefore less predictable.

For the outliers in the data no substantial trend in flight characteristics could be found. However, the number of outliers seem to go up during the airport’s busy times. From this data it can be concluded that the deviation of the ELDT from the ALDT in the outliers can be explained by flights being delayed in-air. This would not be reflected in the ELDT because ABI-1 is sent before the aircraft arrives at the IAF.

**ACT-message**

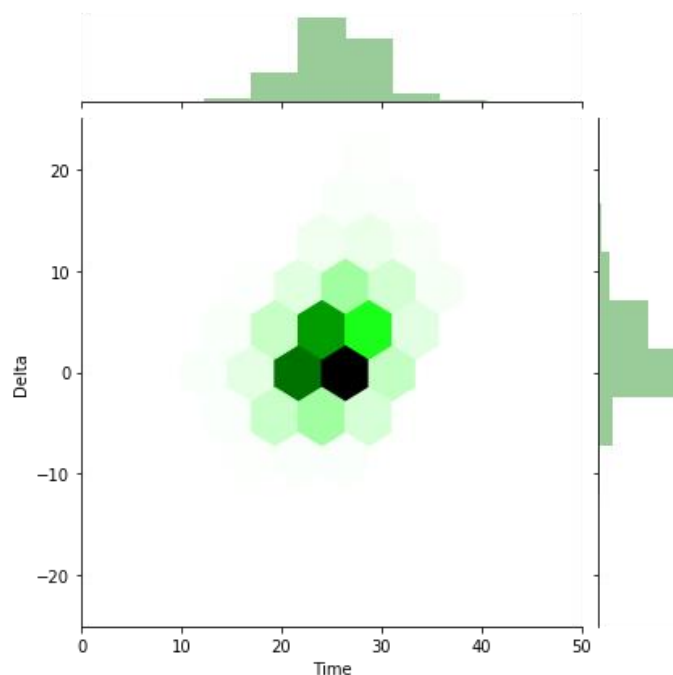


Figure 28 - Time of receipt against accuracy of ELDT ACT

Figure 28 shows the hexagonal binning plot with the ELDT accuracy against the time of receipt of the data. It shows the compact area in which the data is concentrated. Most data is located between the 20-30 minutes mark, and around the 0 minutes deviation.

Table 15 shows the measures of central tendency and spread for the ACT ELDTs. On average the ELDT's deviate  $\pm 2$  minutes from the ALDT. However, including outliers, the accuracy can range from 51 minutes early to three hours late. Given the standard deviation of  $\pm 4$  minutes, it can be concluded that 99.6% of ELDTs deviate from -11.5 to 15.5 minutes. Because the median value of 1,5 minute is only slightly off the mean, it can be concluded that the outliers in the data don't affect the results much. No significant differences between seasons can be spotted.

	Winter	Summer
<b>Count</b>	96.531	152.901
<b>Mean</b>	00:01:57	00:02:09
<b>Standard deviation</b>	00:04:07	00:04:29
<b>Min</b>	-00:51:07	-01:00:00
<b>Max</b>	01:50:58	02:59:39
<b>Median</b>	00:01:28	00:01:30
<b>Outliers</b>	3.45%	4.02%

Table 15 - Accuracy analysis ACT

When dividing the flights per sector, it becomes clear that on average the difference between the accuracy of the ELDT between the entry sectors is less than one minute. However, there are some differences in range. Sectors 1 and 2 both have minimum values of roughly minus 45 minutes, Sector 3 minus one hour, Sector 4 minus 25 minutes and Sector 5 minus 34,5 minutes. The maximum value also varies from three hours to one hour and five minutes. These differences are caused by the outliers in the data, because the spread is the same for all five sectors. The natural difference in traffic in the sectors can be seen in the count row. Note that because the ACT-message is mandatory, the sample size is the same as the total number of flights per sector. Because the five sectors are so equal, they do not differ much from the population.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	38.927	65.803	66.604	37.487	40.568
<b>Mean</b>	00:01:38	00:01:50	00:01:55	00:02:43	00:02:33
<b>Std. dev.</b>	00:04:09	00:04:19	00:04:24	00:04:22	00:04:20
<b>Min</b>	-00:45:47	-00:43:27	-01:00:00	-00:25:04	-00:34:30
<b>Max</b>	01:18:43	01:52:45	02:59:39	01:05:40	02:59:21
<b>Median</b>	00:01:03	00:01:13	00:01:21	00:02:06	00:02:01
<b>Outliers</b>	3.86%	4.08%	4.06%	4.76%	4.48%

Table 16 - Accuracy analysis per entry sector ACT

In the number of outliers, some differences can be seen. Sector 1 and 2 have relatively low numbers of outliers, while in Sector 4 4.76% of flights are considered an outlier.

When the flights are divided per WTC, some notable differences become clear. The mean across the groups is roughly the same, however the minimum and maximum value are not. The range of the Medium (M) and Heavy (H) groups are considerably larger than from the Super (J) category. Furthermore, the number of outliers is also higher in these groups compared to the Super (J) group. This would mean that the landing times of Super (J) category aircraft are more predictable compared to the others. However, due to the difference in sample size, this could also be contributed to randomness considering that the data without outliers is fairly similar.

	Medium	Heavy	Super
<b>Count</b>	203.751	43.549	808
<b>Mean</b>	00:02:00	00:02:23	00:02:15
<b>Standard deviation</b>	00:04:20	00:04:21	00:03:51
<b>Min</b>	-01:00:00	-00:43:27	-00:07:41
<b>Max</b>	02:59:39	02:59:21	00:27:55

<b>Median</b>	00:01:25	00:01:45	00:01:39
<b>Outliers</b>	3.83%	3.96%	1.96%

Table 17 - Accuracy analysis per WTC ACT

When looking at the characteristics of flights that are considered an outlier, some notable differences can be seen compared to the population. Figure 29 shows the difference of IAF distribution of the outliers compared with non-outliers. There is a +12% increase in flights that use SUGOL as their IAF. SUGOL is used as IAF by flights coming from Sector 4 and 5.

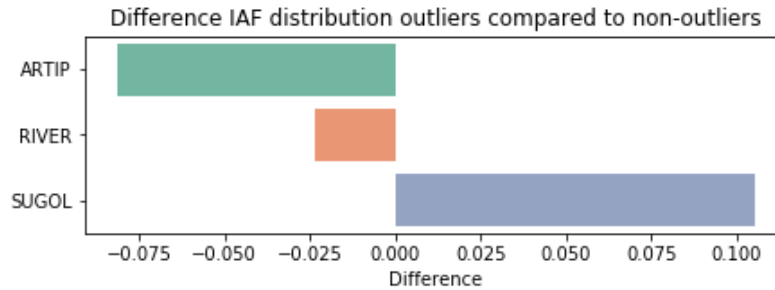


Figure 29 - Difference IAF distribution outliers compared to non-outliers

Because there are no notable differences in WTC and departure airports, it can be concluded that flight characteristics itself do not influence the accuracy of the ELDTs. This leaves three possibilities: the London ATC unit sends out inaccurate data (which is supported given the less accurate ELDTs on average on Sector 4 and 5), flights encounter more route changes than other sectors, or flights arrive with delays that is not reflected into the ELDT. Figure 30 shows the ratio of number of outliers compared to non-outliers per hours in UTC. The same peak at the 8<sup>th</sup> hour from ABI-1 can be seen for ACT. This would support the assumption that delays happen more frequently at Schiphol at that hour.

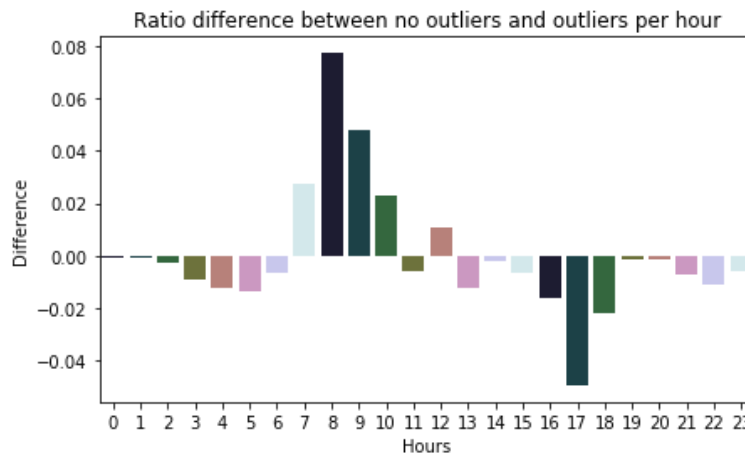


Figure 30 - Ratio difference between no outliers and outliers per hour

**Conclusion ACT-message**

The ACT-message provides reliable and accurate data to calculate an ELDT from. With an average deviation from the ALDT of two minutes, and relatively low spread of data it is quite predictable. This is further supported by the fact that there seem to be no significant differences when comparing entry sectors and WTCs, except for a bit more inaccuracy in sectors 4 and 5.

However, when analysing the outliers specifically, some interesting observations can be seen. Compared to the population there is a +12% increase in flights that use the SUGOL initial approach fix point, originating from sectors 4 and 5. However, no trends can be seen when analysing the WTC and departure airports distribution. This leads to the conclusion that the unpredictability is caused by the London FIR itself. This can be because of inaccurate data send, or more than usual route changes in these sectors that is not reflected in the calculated ELDT. Furthermore, a peak in flights arriving between 07:00 and 10:00 UTC can be seen. These are some of the busiest hours at Schiphol. Delays can therefore be a reason for the deviation between the ELDT and the ALDT.

**Radar correlation**

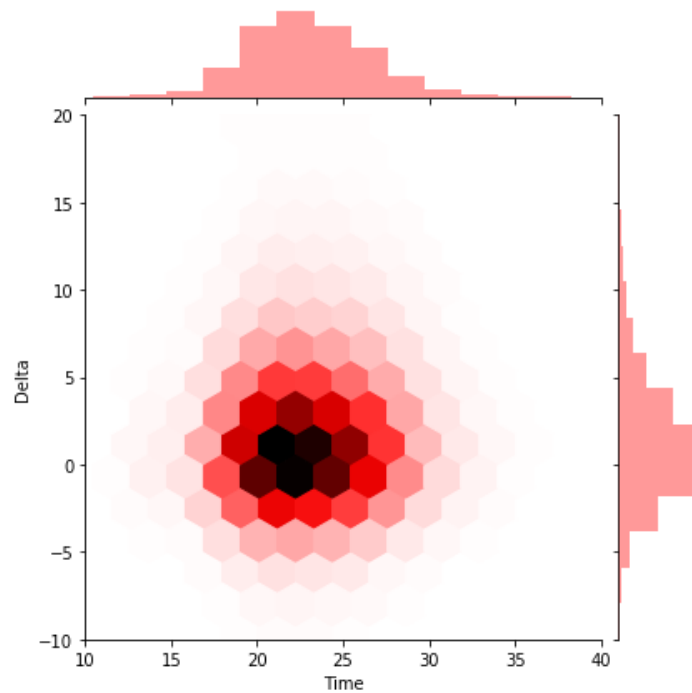


Figure 31 - Time of receipt against accuracy of ELDT radar correlation

Figure 31 shows the hexagonal binning plot with the ELDT accuracy against the time of receipt of the data. It shows that the data is concentrated in a compact area. The distribution bins show that the data follows a normal distribution within that area. Compared to the others, the radar correlation data is closer together. As such, the scale of the axis is less. The accuracy data shows a slightly left skewed distribution, meaning that the ELDT tends to have a positive (aircraft is late) deviation.

Table 18 shows the measures of central tendency and spread for the ELDT’s accuracy generated by radar correlation data. On average the ELDTs deviate roughly one minute 25 from the ALDT. The minimum value is 42 minutes early and the maximum value 59 minutes. Given the standard deviation is ±4 minutes, 99.6% of ELDTs accuracy ranges from -11.5 to 13.5 minutes. The 50% quartile sits at around one minute. 4.22% of the ELDTs are considered an outlier.

	Winter	Summer
<b>Count</b>	96.208	149.652
<b>Mean</b>	00:01:19	00:01:34
<b>Standard deviation</b>	00:03:54	00:04:15
<b>Min</b>	-00:33:08	-00:42:29
<b>Max</b>	00:59:04	00:59:31
<b>Median</b>	00:00:54	00:00:58
<b>Outliers</b>	4.22%	4.22%

Table 18 - Accuracy analysis radar correlation

When dividing the flights into groups per entry sector, it becomes clear that the accuracy of the ELDTs are fairly equal among the entry sectors. The average deviation is around 1.5 minutes for all sectors, with a seven seconds dip in *Sector 5*. The spread of the data is roughly the same, with a standard deviation of ±4 minutes, and the median value is on the one second mark. On the minimum value however, there are some differences. In *Sector 1* and *4* the deviation can be as low as minus 30 minutes, while, for *Sector 2* and *3* the deviation can be minus 42 minutes. Because all groups are equal, they do not differ much from the population.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	38.507	64.839	65.442	36.924	40.112
<b>Mean</b>	00:01:29	00:01:30	00:01:29	00:01:30	00:01:23
<b>Std. dev.</b>	00:04:07	00:04:07	00:04:08	00:04:06	00:00:05
<b>Min</b>	-00:30:24	-00:42:39	-00:42:30	-00:29:57	-00:37:14
<b>Max</b>	00:59:04	00:49:54	00:55:07	00:59:31	00:53:28
<b>Median</b>	00:00:55	00:00:58	00:00:57	00:00:55	00:00:52
<b>Outliers</b>	4.36%	4.49%	4.33%	4.25%	4.46%

Table 19 - Accuracy analysis per entry sector radar correlation

Table 20 shows the measures of central tendency and spread for the flights grouped on WTC. Only marginal differences in mean and spread can be seen compared to the population. However, the 50% percentile of the *Super (J)* group does differ by about 20 seconds. Furthermore, the range of the *Super (J)* group data is less than from the *Medium (M)* and *Heavy (H)* group. The outliers in the *Super (J)* group are relatively high compared to the other groups and population.

	Medium	Heavy	Super
<b>Count</b>	200.606	43.147	797
<b>Mean</b>	00:01:30	00:01:20	00:01:40
<b>Standard deviation</b>	00:04:08	00:04:02	00:04:11
<b>Min</b>	-00:42:37	-00:28:17	-00:11:08
<b>Max</b>	00:59:31	00:49:54	00:33:09
<b>Median</b>	00:00:58	00:00:49	00:01:16
<b>Outliers</b>	4.32%	4.40%	5.37%

Table 20 - Accuracy analysis per WTC radar correlation

When looking at the distribution of flight characteristics in the outliers, a few characteristics stand out. First, there is an increase in flights from *Sector 4* compared to the population. Furthermore, there is an increase in German and UK inbound flights. Together with the fact that the WTC distribution stays roughly the same in the outliers, this leads to the conclusion that flights from Germany and the UK are more unpredictable. But also, that intercontinental flights from *Sector 4* are affecting the accuracy. The increase would however, not be clear because it is offset by the increase in short-haul flights with higher frequency.

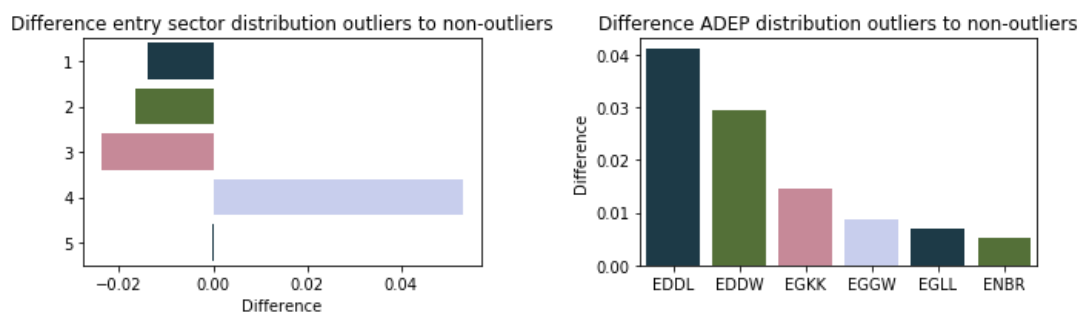


Figure 32 - Difference entry sector and ADEP distribution outliers to non-outliers

In relation to the moment of arrival, the radar groups behave the same way as the ACT-groups, with a peak between 07:00 and 10:00 UTC as shown in Figure 30.

### Conclusion radar correlation

Radar correlation data provides an accurate and predictable ELDT, with an average deviation from the ALDT of roughly 1.5 minutes. With a relatively small range, and tight spread of data it is quite predictable. This is also supported by the fact that there are no significant differences with the population compared to the groups based on WTC and entry sector.

The outliers however, provide an interesting conclusion. In the outliers, there is an increase in flights from *Sector 4* of 5%. However, when comparing the origin of the flights, there seem to

be no big increase in UK airports. Instead, German airports make up the two biggest increases. Because the WTC distribution stays roughly the same, it leads to the conclusion that flights in the outliers arrive from *Sector 4* but do not necessarily have the UK as their origin. Intercontinental flights could be the cause of this, because their increase would be offset by short-haul flights with higher frequencies.

Besides this, a high percentage of flights in the outliers are arriving between the hours of 07:00 and 10:00 UTC, compared to the population. Delays can therefore also be the cause of the more unpredictable deviation from the ALDT.

### FUM-message

ELDTs from FUM-messages are special, because the ELDT is not generated from data within the message but instead the ELDT is part of the message. Table 21 shows the measures of central tendency and spread for all three FUM's. Notable is that even though the accuracy is expected to be more accurate when more updates are given, this is only marginal the case.

For FUM-1, the average deviation from the ALDT is roughly  $\pm 5$  minutes. With a standard deviation of 16 to 18 minutes depending on season the data has a large spread. This is also reflected in the total range of almost more than six hours. Because the median itself is within two minutes from the mean, outliers are the cause of the large spread. Outliers represent 6.78% to 8.04% of data.

For FUM-2, the average deviation from the ALDT ranges from four to five minutes. Like FUM-1 the data has a large spread with a total range of more than six hours. The percentage of outliers is roughly 8% on average between the seasons.

For FUM-3, the average deviation from the ALDT is roughly four minutes. Like the previous FUM-messages the data has a large spread, with a total range of more than six hours. Outliers represent 5.71% to 7.04% of data.

Between the messages, there seem to be only a small improvement on average accuracy. Furthermore, the spread in the data becomes marginally less. Because there are no significant differences in accuracy between the FUM-messages, only FUM-1 will be used for further analysis.

	FUM-1		FUM-2		FUM-3	
	Winter	Summer	Winter	Summer	Winter	Summer
<b>Count</b>	95.882	151.582	80.892	127.490	50.331	87.118
<b>Mean</b>	00:05:19	00:04:33	00:05:18	00:03:58	00:04:11	00:03:33
<b>Std. dev.</b>	00:16:13	00:18:29	00:14:22	00:16:35	00:13:26	00:15:56
<b>Min</b>	-03:00:48	-03:13:26	-03:01:02	-03:15:17	-02:49:23	-03:00:12
<b>Max</b>	03:17:07	03:16:55	03:19:37	03:19:37	03:14:55	03:18:25
<b>Median</b>	00:03:57	00:03:28	00:04:16	00:03:25	00:03:43	00:03:31
<b>Outliers</b>	6.78%	8.04%	7.60%	8.59%	5.71%	7.04%

Table 21 - Accuracy analysis FUM

When dividing the flights into groups per entry sector, it becomes clear that the groups are fairly equal. Some differences in the minimum and maximum value can be seen, with *Sector 5* having a minimum of two hours and 44 minutes. Compared to the population, no significant changes can be seen.

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	38.643	65.400	66.249	37.187	39.952
<b>Mean</b>	00:04:45	00:04:50	00:04:58	00:04:55	00:04:40
<b>Std. dev.</b>	00:17:39	00:17:37	00:17:43	00:17:37	00:17:35
<b>Min</b>	-03:05:47	-03:09:45	-03:05:39	-03:13:26	-02:44:35
<b>Max</b>	03:17:07	03:15:28	03:16:55	03:04:46	03:15:46
<b>Median</b>	00:03:37	00:03:39	00:03:40	00:03:43	00:03:37
<b>Outliers</b>	7.50%	7.68%	7.61%	7.69%	7.52%

Table 22 - Accuracy analysis per entry sector FUM-1

When dividing the data per WTC, it becomes clear that some differences between the aircraft categories can be seen. The *Medium (M)* and *Heavy (H)* category follow the same behaviour as the total population. However, in the *Super (J)* group the total range is only two hours and fifteen minutes compared to the six hours in the population. Furthermore, the number of outliers is relatively high (9.23%) compared to the population.

	Medium	Heavy	Super
<b>Count</b>	202.796	42.557	798
<b>Mean</b>	00:04:52	00:04:41	00:04:51
<b>Standard deviation</b>	00:17:34	00:17:56	00:16:07
<b>Min</b>	-03:13:26	-03:05:24	-01:15:38
<b>Max</b>	03:17:07	03:04:46	01:32:39
<b>Median</b>	00:03:40	00:03:34	00:03:49
<b>Outliers</b>	7.53%	7.96%	9.23%

Table 23 - Accuracy analysis per WTC FUM-1

When looking at the flight characteristics distribution in the outliers, a pattern begins to form. First, in the outliers there is an increase of 15% in distribution compared to population of flights operated with *Medium (M)* category aircraft. Furthermore, most of these flights come from *Sector 4*. This is shown in Figure 33.

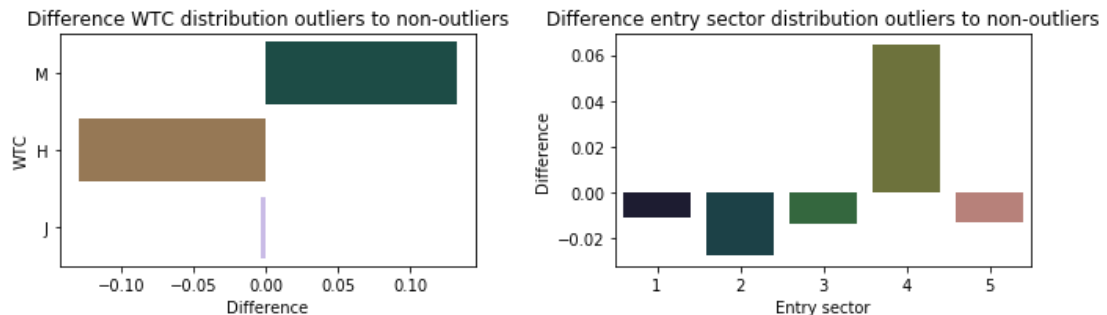


Figure 33 - Difference WTC and entry sector distribution outliers to non-outliers

When filtered further, it becomes clear that in the outliers an increase in distribution is for flights operated by EasyJet (+3%), Flybe (+1.75%), British Airways (+1%), and Delta Airlines (+1%). What these airlines have in common is that they all operate westbound flights, through *Sector 4*. Figure 34 shows the distribution of arriving flights per hour. In contrary to the other data sources, a peak can be seen between 16:00 and 21:00 UTC. Considering that these hours are not the busiest of the day, it is unlikely that the ELDTs deviation from the ALDT can be attributed to delays.

This leads to the conclusion that flights from *Sector 4* are more unpredictable, without there being an obvious reason.

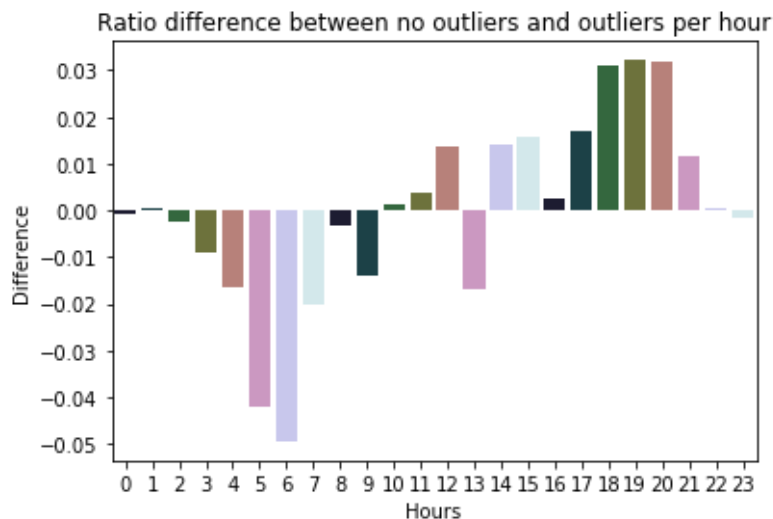


Figure 34 - Ratio difference between no outliers and outliers per hour

**Conclusion FUM-messages**

ELDTs from FUM-messages provide an early estimation of the landing time, at the cost of less accuracy. Even though on average the deviation from the ALDT is around the 4-5 minutes mark, the large spread in the data suggest that it is more unpredictable than the other data sources. This is also reflected in the number of outliers, ranging from 5.71% to 8.59%.

The average accuracy does not seem to be affected by the entry sector or the WTC, since both flight characteristic groups seem to follow the same behaviour as the population. Some differences can be seen in the *Super (J)* category group, which have less range in the data. However, this is most likely due to less randomness caused by the significant smaller sample size.

When analysing the outliers, it becomes clear that flights originating from *Sector 4* have less predictable ELDTs. This seems especially true for flights from the UK and Ireland operated by *Medium (M)* category aircraft, with increases for EasyJet (+3%), Flybe (+1.75%), and British Airways (+1%). However, Delta Airlines also sees an increase of +1%. This is in line with the fact that *Sector 4* sees a lot of intercontinental traffic. It can therefore be concluded that the unpredictability is not necessary caused by the geographical location but more so caused by the London FIR itself. An analysis in the time of arrival shows that a relatively high distribution of outliers is located between 17:00 and 21:00 UTC. In contrary to previous data sources, these are not considered peak hours at Schiphol. The effect of delays due to a crowded airspace is therefore neglectable.

**Conclusion accuracy analysis ABI-1, ACT, FUM, and radar correlation**

Between the data sources varies degrees of accuracy can be seen. However, most of them (ABI, ACT, and radar correlation) are on average within two minutes from each other, with radar correlation being the most accurate followed by the ACT, ABI, and FUM ELDTs. Besides being accurate, the ELDTs are also fairly predictable with small spreads of data and low numbers of ELDTs classified as outliers. ELDTs provided by FUM-messages are an exception with large spread, and a total deviation range of six hours. Furthermore, the number of outliers is also considerably higher ( $\pm 7\%$ ) than of the other data sources.

When dividing the flights into groups per entry sector, some interesting observations can be seen. ABI-1 ELDTs are on average within a minute of the ALDT, except for flights from sectors 4 and 5. The same behaviour can be seen in the ACT ELDTs, but on a smaller scale. The accuracy of radar correlation and FUM ELDTs is roughly equal across all five sectors.

When the flights are divided into groups of WTCs, some differences can also be spotted, although it being marginal. Most notable is that ABI and ACT ELDTs for flights operated by *Medium (M)* category aircraft are the most accurate. In radar correlation and FUM ELDTs *Heavy (H)* aircraft have the most accurate ELDTs.

As stated in previous section, outliers represent a small percentage of the total flights. However, it is useful to understand if there is a trend based on flight characteristics in the outliers. When analysing the distribution of these flight characteristics in the outliers, there is one trend in all data source analyses: an increase in distribution compared to the population of flights from sectors 4 and 5, following the SUGOL initial approach fix. This is true for both intercontinental as continental traffic. Furthermore, depending on the data source peaks can be seen on arrival times. Except for the FUM ELDTs, most outlier flights arrive during 07:00 and 10:00 UTC which are considered busy hours. FUM outliers have high distribution between 17:00 and 21:00 UTC.

This leads to the conclusion that the deviation from the ALDT in both sectors 4 and 5 can be attributed to a cause inside the London FIR (route changes, inaccurate data, busy airspace) which are not taken into account in the ELDT calculation or a delay caused by busy airspace around Schiphol.

## 7 Discussion and Conclusions

### 7.1 Conclusions

The aim of this research was to understand what causes outliers in both time of receipt of sources of information, and accuracy of the ELDTs, specifically looking at the two main flight characteristics: entry sector and WTC. The following main research question was formulated:

*“How do flight characteristics affect the accuracy and time of receipt of ABI, ACT, FUM, and radar correlation data, to which the landing time estimations are based on?”*

Research started with a throughout desk research into how information from data sources is used by what systems. During the pre-planned phase, two LVNL systems are capable of producing an ELDT: AAA and ASAP. The latter is a module inside the overarching AAA system.

The data analysis part of the research is divided into three phases, a general overview of the dataset, an analysis into the frequency and time window of sources of information, and an analysis into the accuracy of the ELDTs. Analysing the outliers specific is a focus point for this research. The dataset that was analysed contained 249.438 arriving flights during the period of the 28<sup>th</sup> of October 2018 until the 30<sup>th</sup> of October 2019. 96.532 of these flights arrived during the winter of 2018/2019, and 152.906 flights during the summer of 2019. From the total number of flights 223.125 were operated by *Medium (M)* category aircraft, 47.552 by *Heavy (H)*, and 869 by *Super (J)* category aircraft. 42.690 flights originated from *Sector 1*, 72.025 from *Sector 2*, 72.900 from *Sector 3*, 40.988 from *Sector 4*, and 44.362 from *Sector 5*.

The analysis on the reception of data sources have shown that not all data sources are received equally. Only 71.90% of times ABI-1 is received. For FUM-messages, the first one is received 99.67% of times, FUM-2 91.47%, and FUM-3 75.67%. ACT-messages and radar correlation data is received 100% of times. When looking at the reception rate per WTC and entry sector, notable differences are seen. ABI-1 is received only 68.54% for *Medium (M)* aircraft, while *Heavy (H)* and *Super (J)* aircraft receive it 91.69% and 99.70% of times. Furthermore, *Sector 3* sees only a 4.02% reception rate of ABI-1. When looking specifically at flights that did not receive ABI-1, these flights came from few specific airports, namely: Bremen, Dusseldorf, Hannover, London Stansted, Humberside, and Norwich. These airports are all geographically close to Schiphol. It is not unheard of for short distance flights to not receive an ABI-message. Because ABI transmission is blocked when the ACT-message is to be sent immediately after or within a bilaterally agreed upon time window, or when the flight distance to the FIR border is too short (thus producing a PAC-message) it is possible that this is the reason for the lack of ABI-1 reception. However, not all flights from these airports did not receive ABI-1 suggesting this is not always the reason.

From the flights that did not receive FUM-1, an increase in distribution compared to the “normal” situation is seen in intercontinental flights from New York JFK, Atlanta, Washington Dulles, and Detroit specifically. Flights that did not receive FUM-1, also did not receive FUM-2 and FUM-3. Notable is that these airports are all in the United States. Because FUM ELDTs are generated from information received by Eurocontrol from the different ANSPs and AOs, it is a possibility that the FUM-message was validated as erroneous, thus deleting the message. This is supported by the fact that for less than 1% of flights no FUM-message was received.

The time window analysis also revealed mixed results. ABI-1 is received on average 39 minutes before arriving at IAF. However, notable is that *Sector 4* flights generally receive ABI-1 five minutes later than the population. This seem to be the case for airports that are located close to the sea border specifically, with airports further east being less affected. The geographical distance between the departure airport and Schiphol seem to affect when ABI-1 is sent. Furthermore, even though *Sector 3* has low reception of ABI-1, 88% of flights that do receive it are from the Air France-KLM group. For ACT, only marginal differences could be seen when looking at the outliers. An +7% increase in *Medium (M)* aircraft distribution, +5% increase for sectors 2, and 3, and +2% increase in *Sector 5* traffic is seen. Airports close to the Dutch border make up a relatively high percentage of flights with Brussel (+13%) and Dusseldorf (+8%) being the top ones.

In the analysis of the three FUM-messages it became clear that all three FUMs behave in a different way. This leads to believe that specific flight characteristics do not affect the forming of outliers much, but that the cause lays with Eurocontrol. Research into what events trigger a FUM is needed to clarify this.

The results from the accuracy analysis have shown that accuracy of ABI, ACT, and radar correlation ELDTs are affected by the time of arrival of the flight. During the busy hours of 07:00 to 10:00 UTC, most outliers are formed. Furthermore, one reoccurring conclusion is that flights from *Sector 4* and 5 have more unpredictable landing times. No significant increase in airline or departure airport distribution could be found, what leads to the conclusion that the London FIR itself is the cause of the problems. Route changes, delays in airspace, or inaccurate data sent can all three be a possibility of why most outliers come from sectors 4 and 5.

## 7.2 Discussion

Research into the outliers have resulted into interesting observations. Challenging for the research was to formulate a proper scope and subject area, during a time where face-to-face communication is impossible. Because of this, the research is very quantitative *Heavy (H)* and lack the depth of having a proper discussion with business experts.

In the beginning, it was not clear if there would be significant differences in accuracy or time of receival when comparing flight characteristics. Even though, given the nature of some data sources, some results were expected some of them did not work out. This is especially true for the analysis of the FUM-message were an increase in accuracy is expected in further update messages. However, average accuracy stayed roughly the same through FUM-1 to FUM-3. The lack of consistent justification of why outliers form in the time window analysis of FUM-messages is also not expected. This leads to one of the limitations in the research, most “problem” areas are not in the scope of LVNL, but caused by a foreign ATC unit. Directly solving the issues is therefore not an option.

Further limitations were the lack of proper hypothesis testing. Even though it is now known that certain flights with specific flight characteristics are more present in the outliers, it is not known whether this is due to chance or not. This is especially true for outliers with only a marginal increase in distribution.

Follow-up research into why *Sector 4* and 5 generally seem to be the problem when it comes to accuracy is needed. This is preferable done with a qualitative research structure in mind. Furthermore, only four data sources are used in this research, more research into new data sources such as ACARS could be interesting to compare with.

## 8 Recommendations

In this chapter, recommendations are made to the company to improve the predictability of the landing times based on the results of the analyses. Because there is such a difference in cause of outliers between the different types of outliers no general solutions can be offered.

### ***Lack of 100% ABI-message receipt***

One of the observations is that for airports that are geographically close to Schiphol in some cases the ABI-message is not received. When ABI transmission is overlapping with ACT transmission, or if it is within the agreed time interval the adjacent ATC unit will not send an ABI. Because this is dependent on the flight distance between the airport and the FIR border, it is expected that all flights from these destinations do not receive ABI. However, this is only the case for a small portion of the flights. An assessment of the current bilateral agreements between LVNL and adjacent centres could be useful to understand why these flights in particular did not receive the ABI-message.

Furthermore, because ABI reception in *Sector 3* is close to noon a different data source prioritization should be used for this sector. Currently between ABI and ACT reception the FUM ELDTs can be used (or ACARS when it involves a KLM flight). (Scheffers, 2020) However, FUM ELDTs are less accurate than both sources. Further research into whether radar correlation ELDTs can be used to act as a “bridge” until the ACT-message is received, could be useful because this allows for a better estimation of the landing times.

### ***ELDTs received from Sector 4 and Sector 5***

One overarching theme in the results is that the accuracy of ELDTs for flights from *Sector 4* and *Sector 5* are less accurate and contain more outliers than other sectors. Besides the accuracy analysis, there are also more outliers found in these sectors for the time window analysis. Because flights from these sectors all originate from the London FIR, it is possible that the “problem” lies with them. Further research into the agreements between the London ATC unit and LVNL could help solve the unpredictability of the ELDTs from these sectors.

### ***FIR delay component in ELDT calculations***

From the ABI, ACT, and radar correlation results it became clear that the ELDTs become less accurate during the morning period of 07:00 and 10:00 UTC. This coincides with the intercontinental arrival wave from the east. When calculating the ELDTs the expected FIR delay is taken into account. However, it is interesting to see that the ELDT accuracy is only negatively affected during the morning wave, and not during the later peak hours. Further research into why particularly this wave is the cause for the forming of outliers could help further improve the ELDT generation algorithm for the future.

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## Appendix A Dataset variables

Column name	Description	Example
<b>Date</b>	Date of flight	20181001
<b>EOBT</b>	Estimated On-Block-Time in epochs format	1538320200
<b>Acid</b>	Flight ID	KLM894
<b>Airline</b>	Airline name	KLM
<b>ADEP</b>	Departure airport	ZSPD
<b>ADES</b>	Arriving airport	EHAM
<b>A/C_type</b>	Aircraft type	B789
<b>WTC</b>	Wake turbulence category	H
<b>Entry_sector</b>	CTA of entry	1
<b>STAR_id</b>	Standard arrival route ID	EEL1A
<b>IAF_name</b>	Initial Approach Fix	ARTIP
<b>Time_IAF</b>	Time aircraft arrived at IAF	1538359777
<b>Time_ABI1_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI1_AAA</b>	ELDT based on data source	1538359777
<b>Time_ABI2_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI2_AAA</b>	ELDT based on data source	1538359777
<b>Time_ABI3_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI3_AAA</b>	ELDT based on data source	1538359777
<b>Time_ABI4_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI4_AAA</b>	ELDT based on data source	1538359777
<b>Time_ABI5_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI5_AAA</b>	ELDT based on data source	1538359777
<b>Time_ABI6_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ABI6_AAA</b>	ELDT based on data source	1538359777
<b>Time_ACT_AAA</b>	Time of data receipt	1538359777
<b>ELDT_ACT_AAA</b>	ELDT based on data source	1538359777
<b>Time_FUM1_AAA</b>	Time of data receipt	1538359777
<b>ELDT_FUM1_AAA</b>	ELDT based on data source	1538359777
<b>Time_FUM2_AAA</b>	Time of data receipt	1538359777
<b>ELDT_FUM2_AAA</b>	ELDT based on data source	1538359777
<b>Time_FUM3_AAA</b>	Time of data receipt	1538359777
<b>ELDT_FUM3_AAA</b>	ELDT based on data source	1538359777
<b>Time_radar_AAA</b>	Time of data receipt	1538359777
<b>ELDT_radar_AAA</b>	ELDT based on data source	1538359777
<b>Time_slot_AAA</b>	Time of data receipt	1538359777
<b>ELDT_slot_AAA</b>	ELDT based on data source	1538359777
<b>ALDT</b>	Actual Landing Time	1538359777
<b>ELDT_ABI_ASAP</b>	ELDT based on data source ASAP	1538359777
<b>ELDT_ACT_ASAP</b>	ELDT based on data source ASAP	1538359777
<b>Predicted_rwyt</b>	Predicted Runway	6
<b>Actual_rwyt</b>	Actual Runway	27R

## Appendix B Time window boxplots

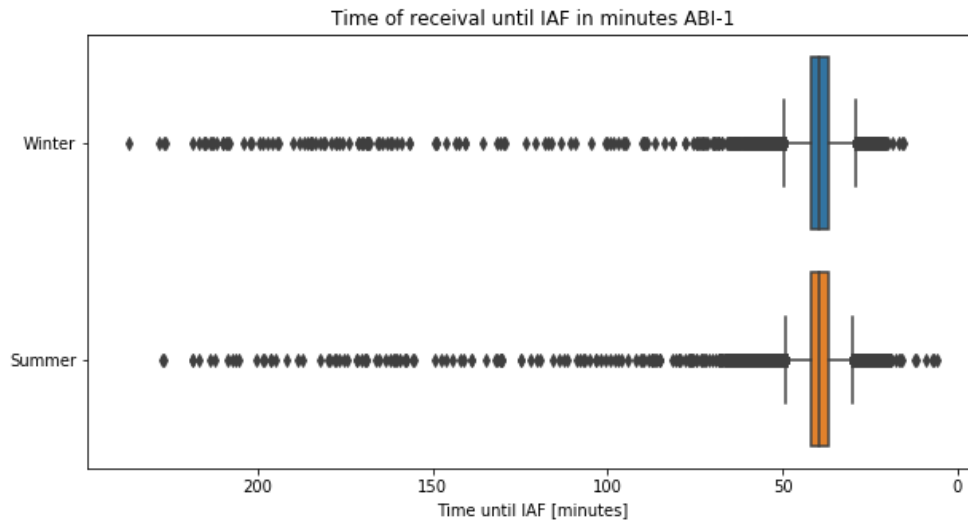


Figure 35 - Boxplots time of receipt until IAF in minutes for ABI-1

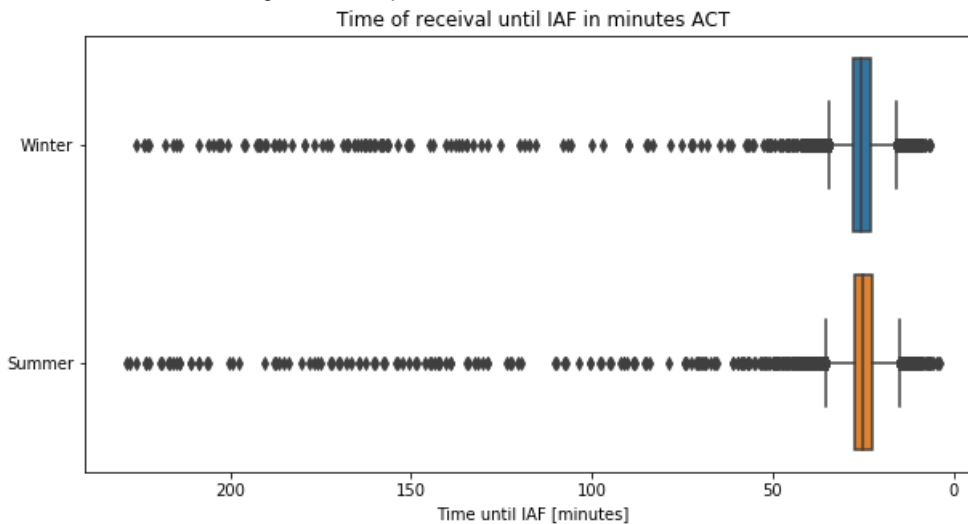


Figure 36 - Boxplots time of receipt until IAF in minutes for ACT

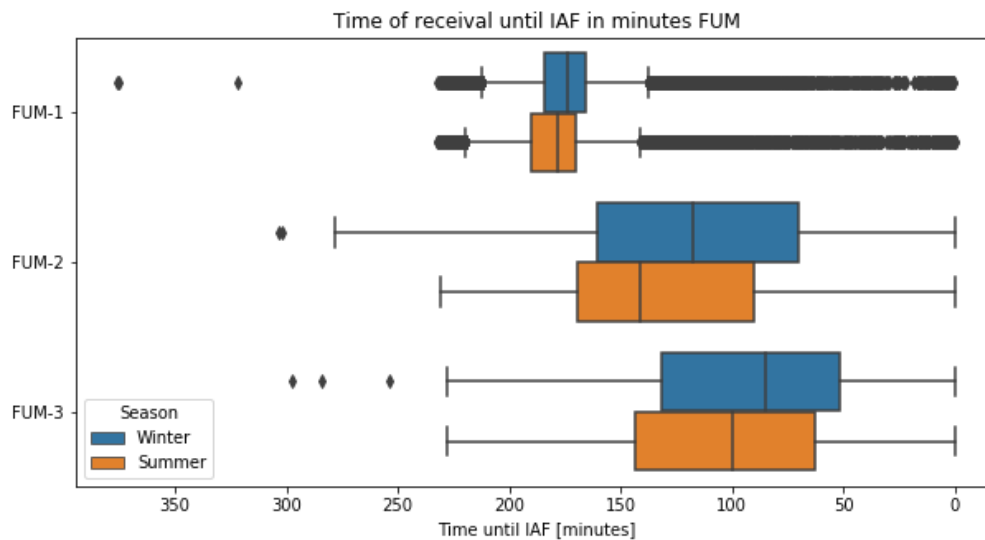


Figure 37 - Boxplots time of receipt until IAF in minutes for FUM

## Appendix C Descriptive statistics FUM reception

	Winter					Summer				
	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	15.014	25.048	24.854	15.903	15.343	23.678	40.849	41.384	21.672	24.581
<b>Mean</b>	02:58:03	02:59:18	02:54:20	02:54:19	02:53:57	03:00:01	03:03:57	02:59:08	02:59:21	02:59:46
<b>Std. dev.</b>	00:19:04	00:17:48	00:17:27	00:20:24	00:20:11	00:17:21	00:17:29	00:17:10	00:19:44	00:19:36
<b>Min</b>	00:02:16	00:00:52	00:03:30	00:00:04	00:00:48	00:00:13	00:00:31	00:03:01	00:00:07	00:00:00
<b>Max</b>	06:15:31	06:15:49	03:50:40	03:51:24	03:52:13	03:50:22	03:52:01	03:51:58	03:51:30	03:50:54
<b>Median</b>	02:54:58	02:56:34	02:51:19	02:52:22	02:52:43	02:57:21	03:01:55	02:56:31	02:57:01	02:57:30
<b>Outliers</b>	0.04%	0.04%	0.08%	0.06%	0.07%	0.04%	0.01%	0.05%	0.05%	0.05%

Table 24 - Time window analysis per entry sector FUM-1

	Winter					Summer				
	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	13.966	22.884	24.041	14.296	12.298	22.476	38.063	40.482	18.914	18.477
<b>Mean</b>	02:00:06	02:09:12	02:05:32	01:33:10	01:24:18	02:07:52	02:20:49	02:15:04	01:58:47	01:43:56
<b>Std. dev.</b>	00:49:26	00:45:57	00:41:18	00:59:14	00:51:16	00:47:37	00:44:23	00:39:43	01:01:23	00:55:48
<b>Min</b>	00:00:09	00:00:00	00:00:07	00:00:00	00:00:00	00:00:01	00:00:00	00:00:13	00:00:07	00:00:00
<b>Max</b>	05:03:07	05:02:06	03:48:42	03:50:34	03:48:09	03:47:07	03:50:43	03:48:21	03:48:49	03:44:48
<b>Median</b>	01:58:40	02:18:16	02:11:03	01:13:07	01:01:52	02:12:45	02:35:48	02:21:49	02:16:14	01:36:43
<b>Outliers</b>	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 25 - Time window analysis per entry sector FUM-2

	Winter					Summer				
	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5
<b>Count</b>	10.681	17.321	20.472	11.641	8.231	18.156	29.262	35.822	16.505	14.024
<b>Mean</b>	01:38:05	01:41:13	01:42:10	01:10:55	01:09:55	01:40:35	01:51:33	01:51:13	01:30:01	01:21:20
<b>Std. dev.</b>	00:46:50	00:48:07	00:43:04	00:57:13	00:46:14	00:48:10	00:46:31	00:43:50	00:50:37	00:44:11
<b>Min</b>	00:00:01	00:00:03	00:00:03	00:00:01	00:00:00	00:00:04	00:00:01	00:00:01	00:00:03	00:00:01
<b>Max</b>	04:57:31	04:44:12	03:45:37	03:48:15	03:44:51	03:46:48	03:47:43	03:48:04	03:46:58	03:40:37
<b>Median</b>	01:29:52	01:33:00	01:44:19	00:47:55	00:54:24	01:32:52	01:49:25	01:54:37	01:12:42	01:01:45
<b>Outliers</b>	0%	0%	0%	0%	0%	0%	0%	0%	0.01%	0.08%

Table 26 - Time window analysis per entry sector FUM-3

