Master Thesis

Cross-Border Arrival Management to Reduce Traffic Bunching at Schiphol Airport

M. van Horssen

June 16, 2017

Faculty of Aerospace Engineering · Delft University of Technology

TU Delft Delft University of Technology

Challenge the future

Cross-Border Arrival Management to Reduce Traffic Bunching at Schiphol Airport

Master Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

M. van Horssen

June 16, 2017

Faculty of Aerospace Engineering · Delft University of Technology

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Delft University Of Technology
Department Of
Control & Simulation

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Cross-Border Arrival Management to Reduce Traffic Bunching at Schiphol Airport"** by **M. van Horssen** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: June 16, 2017

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Acronyms

AAA	Amsterdam Advanced ATC
AAH	Active Advisory Horizon
ACC	Area Control Centre
EHAA	Amsterdam
AMAN	Arrival Management
ANSP	Air Navigation Service Provider
APLN	Approach Planner
APP	Approach
ARSIM	AMAN Research Simulator
ASAP	Advanced Schiphol Arrival Planner
ATC	Air Traffic Control
ATFCM	Air Traffic Flow & Capacity Management
ATM	Air Traffic Management
CBAS	Cross Border Airspace
COP	Co-ordination Point
CTA	Control Area
CTR	Control Zone
DDR	Demand Data Repository
EAT	Expected Approach Time
EH	Eligibility Horizon
ETA	Estimated Time of Arrival
ETO	Estimated Time Over
FABEC	Functional Airspace Block Europe Central
FH	Freeze Horizon
FL	Flight Level
IAF	Initial Approach Fix
IBP	Inbound Planning System

LHR	London Heathrow
LIV	Landing Interval
LNAV	Lateral Navigation
LoA	Letter of Agreement
LREH	Long Range Eligibility Horizon
LVNL	Luchtverkeersleiding Nederland
MUAC	Maastricht Upper Area Control
NMOC	Network Manager Operations Centre
R/T	Radio Telephony
SARA	Speed And Route Advisor
SDR	Speed Delay Ratio
STA	Scheduled Time of Arrival
STAM	Short Term ATFCM Measure
STAR	Standard Terminal Arrival Route
SWIM	System Wide Information Management
TAS	True Airspeed
TMA	Terminal Manoeuvring Area
TOD	Top Of Descent
TP	Trajectory Predictor
TWR	Tower
UAC	Upper Area Control
UTC	Universal Coordinated Time
VNAV	Vertical Navigation
XMAN	Cross-border Arrival Management

Contents

List of Figures

List of Tables

Acknowledgements

Vanaf jongs af aan heb ik interesse gehad in ATC en ATM. Met een vader als luchtverkeersleider is de passie en interesse voor de luchtvaart er altijd geweest. Na vele uren in de verkeerstoren als bezoeker tijdens de middelbare school doorgebracht te hebben was het een logisch gevolg om Luchtvaart- en Ruimtevaarttechniek te gaan studeren aan de TU Delft.

Zes jaar later mag ik nu mijn onderzoeksrapport presenteren over het onderwerp cross-border arrival management, met als doel het verminderen van traffic bunching. In de afgelopen maanden heb ik de impact van traffic bunching op het Nederlandse ATM systeem gezien, zowel operationeel als met operationele data. Ik wil op deze manier graag bijdragen om een goede oplossing te vinden om traffic bunching te verminderen.

Mijn dank gaat uit naar Evert Westerveld van Luchtverkeersleiding Nederland (LVNL) voor de begeleiding vanuit de LVNL en het voorzien van deze opdracht. Verder wil ik ook graag Jacco Hoekstra en Joost Ellerbroek van de TU Delft bedanken voor hun tijd en inzet om mij te begeleiden.

Naast mijn begeleiders wil ik Rob Bezemer, ACC controller en supervisor, bedanken voor de mogelijkheid tot het meelopen op Zaal en daarnaast voor de feedback en informatie over traffic bunching en arrival management. De hulp van Theo Hendriks, capacity program manager bij Maastricht UAC, was erg waardevol voor het begrijpen van de huidige procedures bij MUAC en het XMAN programma met London Heathrow. Alina Zelenevska wil ik graag bedanken voor het helpen met de vormgeving van mijn verslag en haar goede feedback op de inhoud van het verslag. Last but not least wil ik Alexander Vanwelsenaere bedanken voor mij op weg te helpen met ARSIM en zijn kennis te delen over AMAN systemen.

Ik kijk met veel genoegen terug op mijn onderzoek, en met trots presenteer ik u mijn Master Thesis Report.

Summary

The last couple of years many research was performed at Schiphol Airport to better predict the inbound traffic. As the traffic is growing, so have the delays. Even though the delays are still within bounds set by the Functional Airspace Block Europe Central (FABEC), regulations are necessary to control the inbound traffic flow. Since regulations only apply to aircraft that have yet to depart, there is a necessity to manage aircraft and apply delay absorption in the cruise phase of flight. In order to apply en-route delay absorption, the FABEC concept of cross-border arrival management (XMAN) is introduced.

When too many aircraft arrive in a limited time frame, traffic bunching occurs. A traffic bunch is defined as a second aircraft crossing Amsterdam (EHAA) Cross Border Airspace (CBAS) (i.e. the planning horizon), within a certain margin of the first aircraft. Traffic bunches, as calculated at the CBAS horizon, add to the (perceived) workload of the air traffic controller. XMAN is deemed as a feasible solution to reduce traffic bunching. This research investigated the feasibility of XMAN for Schiphol Airport to reduce traffic bunching.

Using the BlueSky ATM Research Simulator and the AMAN Research Simulator, traffic flying to Schiphol Airport is simulated. Each simulation run represents a three hour inbound peak. The user can define the planning horizon and the approach margin, and the arrival manager will manage all the aircraft. For each aircraft, the trajectory is predicted, a landing slot is allocated and speed and/or route advisories are given to ensure each aircraft passes the Initial Approach Fix (IAF) at the Expected Approach Time within the approach margin. During the simulation, several variables are recorded to find the impact of the extension of the planning horizon (scenario I), and the impact of applying a tighter approach margin (scenario II) on the arrival manager performance.

The extension of the planning horizon (scenario I) had a positive impact on the amount of low-level delay. The amount of low-level delay decreased and more aircraft could continue into the Terminal Manoeuvring Area (TMA) without absorbing any low-level delay. Unfortunately, the approach sequence was unstable. Both the number of Scheduled Time of Arrival (STA) revisions and the number of sequence changes increased significantly. However, by extending the horizon, almost no sequence changes occurred after the aircraft's Top of Descent. As a result, aircraft can fly an undisturbed descent towards the runway. The TMA operation is not affected, as the inter-arrival time and the IAF accuracy remain constant. By applying en-route speed control, the number of sequences changes per aircraft significantly increased. Lastly, the number of traffic bunches stayed constant and did not appear to be impacted by the extension of the horizon.

The tighter approach margin (scenario II) did not have a significant effect on low-level delay absorption. However, when splitting the low-level delay data per IAF, it was noted a significant increase in number of aircraft subject to a delay absorption strategy was seen. So even though the average low-level delay was the same, more aircraft needed to absorb low-level delay. Looking at the number of STA revisions and the number of sequence changes, both seem to be unaffected. Furthermore, the number of disturbed descents was not changed. The inter-arrival time between aircraft was not affected, however the IAF accuracy increased with a tighter margin. The reason for this increase is that aircraft need to pass the IAF within a tighter margin, and thus the accuracy will increase too. The number of speed changes significantly increased for a tighter margin. With a tighter margin, aircraft will receive speed advisories when the delay is more than 30 seconds instead of waiting until the delay is more than 120 seconds. Last but not least, the number of traffic bunches are not affected by a tighter approach margin.

The main conclusion that can be drawn is that the number of traffic bunches is not affected by an extension of the horizon, and neither by a tighter approach margin. XMAN is therefore not effective to reduce traffic bunching. However, XMAN can support the introduction of en-route delay absorption and thereby reduce the low-level delay. The descent phase of flight will be improved compared to the current situation. The price of using XMAN is the instability in the approach sequence and the increase in speed changes. The instability can be improved by additional research on a delay threshold and the introduction of using front-loading. Next to that, research should be done to evaluate the impact of the additional workload and radio telephony (R/T) on the surrounding centres and upper centres, and how the workload and R/T can be minimised and distributed among the centres.

Chapter 1

Introduction

The traffic at Schiphol Airport has been growing the last couple of years. Between 2011 and 2015, airport traffic increased by 6.5% and en-route traffic increased by almost 6% [FABEC, 2015]. The number of movements has increased to over 1500 movements a day [LVNL, 2016e]. However, with an increase in traffic the amount of delays on the airport increased by 140% [FABEC, 2015]. The delays are still within the bounds set by the Functional Airspace Block Europe Central (FABEC) group. Next to the delays, the workload of the air traffic controller has increased too. The amount of traffic between 2015 and 2016 increased by 6.3%, with a total of 478,864 movements in 2016 [Schiphol Group, 2017]. To accommodate the growth up to 500,000 movements on a yearly basis, a solution should be found to make sure the delays stay within the bounds set by the FABEC group and, preferably, decrease the workload of the controller.

Currently, when too much traffic is expected in a certain time frame, the flow controller at Schiphol Airport will issue a tactical regulation. Tactical regulations will delay non-airborne flights, thereby balancing the demand with the available capacity. Tactical regulations will, however, not affect any airborne flights. In limited situations, speed requests are sent to neighbouring centres to reduce the speed of inbound aircraft to Schiphol Airport. To improve the airborne traffic flow, the FABEC cross-border arrival management (XMAN) concept is introduced. XMAN will cause an extension of the planning horizon and thereby allow the sharing of delay with surrounding air navigation service providers. As a consequence, delays may be absorbed during the cruise phase of flight and the controller benefits as less delay needs to be absorbed in the Dutch airspace.

Twenty minutes before aircraft enter the Dutch airspace, flight plan information is sent to the Luchtverkeersleiding Nederland, the Dutch air navigation service provider. Each aircraft will fly a Standard Terminal Arrival Route from the co-ordination point towards one of the three Initial Approach Fixes (IAFs), while absorbing the necessary delay. Amsterdam Area Control Centre (ACC) controllers will make sure each aircraft passes the IAF at their Expected Approach Time ± two minutes, which is the current approach margin. When too many aircraft enter the Dutch airspace, traffic bunches are seen. These bunches cause an increase in workload for the ACC controllers. To reduce the traffic bunches, the XMAN concept may be introduced at Schiphol Airport. During the Preliminary Thesis [M. van Horssen, 2017], the XMAN concept was analysed and deemed as a feasible solution to de-bunch aircraft. Using the BlueSky ATM Research Simulator and the AMAN Research Simulator, simulations have been performed to analyse XMAN for inbound traffic to Schiphol Airport. In this report, the results of these simulations are presented and discussed. Furthermore, a quantitative answer to the following research question is found:

To what extent is traffic bunching influenced by the use of cross-border arrival management at Schiphol Airport?

This report starts with a summary of the Preliminary Thesis. Chapter 2 summarises the required background information for this thesis, and Chapter 3 gives the research design. Readers who are already familiar with the information presented in the Preliminary Thesis may skip to Chapter 4, where the simulation set-up is introduced and a concise explanation of the BlueSky ATM Research Simulator and the AMAN Research Simulator is given. Chapter 5 presents the results, and thereafter a discussion of these results and the research question is held in Chapter 6. Conclusions on the results are drawn in Chapter 7 and, finally, recommendations on the research topic are stated in Chapter 8.

Chapter 2

Background Information

This chapter is a short summary of the main findings in the Preliminary Thesis [M. van Horssen, 2017]. At first, the project objective is explained. The Dutch airspace with the relevant air traffic controllers is presented in the second section, including the arrival routes to Schiphol Airport. The arrival management system is touched upon in the penultimate section. In the last section, information on flow management, traffic bunches and flight inaccuracy is stated.

2.1 Project objective

The traffic load at Schiphol Airport is managed through a demand and capacity balancing process in which the Network Manager Operations Centre (NMOC, the former Central Flow Management Unit) plays an important role. Regulations can be given for Schiphol Airport, issued by the Luchtverkeersleiding Nederland (LVNL) and executed by NMOC, to avoid capacity overload.

Regulations may balance the demand and capacity using departure slots, meaning only non-airborne traffic is affected. All planned flights towards Schiphol Airport are re-planned in accordance with the available capacity. Due to airport and en-route operations, deviations from the flight schedule may still cause traffic bunches (unpredicted demand peaks or an overload) in the traffic flow. As a result, more regulations on flights coming from nearby airports are necessary to reduce the arrival traffic load.

NATS, the Air Navigation Service Provider (ANSP) of the United Kingdom, claims to have successfully implemented the Functional Airspace Block Europe Central (FABEC) Cross-border Arrival Management (XMAN) concept at London Heathrow (LHR). This concept allows active monitoring of airborne flights. Using the XMAN system at LHR, aircraft will reduce speed while flying towards the holding stack. This reduction causes the aircraft to spend less time in the holding stacks. The full implementation of the XMAN system is explained in Section 2.3.2. At Schiphol Airport, delays are mainly absorbed using tactical vectors, such as speed or heading instructions. Despite the fact that the

LHR operational environment is very different from Schiphol Airport, the concept may have potential to prevent traffic bunches at Schiphol Airport. If tailored right, the FABEC XMAN concept could potentially reduce the need for tactical regulations, offering a more efficient arrival management solution for Schiphol Airport.

2.2 Airspace, air traffic control and arrival routes

In this section, the airspace in the Netherlands, involved air traffic controllers and the arrival routes towards Schiphol Airport are described.

During the en-route phase of flight, many aircraft fly in upper airspace. Above the Netherlands, the upper airspace starts at Flight Level (FL) 245 until FL 600 and is controlled by Maastricht Upper Area Control (MUAC, or Maastricht UAC). The airspace directly below the upper airspace is the control area (CTA), between FL 095 and FL 245. Aircraft will enter the CTA at the co-ordination point (COP). Aircraft flying within the CTA are handled by Amsterdam Area Control Centre (ACC). Amsterdam ACC mostly handles traffic flying to or from the Netherlands. Aircraft towards Schiphol Airport are instructed with a Standard Terminal Arrival Route (STAR) and will fly a fixed route between the COP and the Initial Approach Fix (IAF). When flying over the IAF, aircraft will enter the Terminal Manoeuvring Area (TMA). The TMA starts at 2000 feet until FL 095 and aircraft within the TMA are controlled by Schiphol Approach (APP). Inside the TMA, aircraft are given heading and speed instructions by APP to fly towards the runway. When the aircraft gets closer to the airport, it will enter the control zone (CTR). The CTR is the airspace directly around an airport between the ground and 3000 feet. Once the aircraft is lined up with the runway by APP and has entered the CTR, Schiphol Tower (TWR) will give a landing clearance. A horizontal overview of the Dutch airspace can be found in Figure 2.1. [LVNL, 2016a, J.M. Hoekstra and J. Ellerbroek, 2016b]

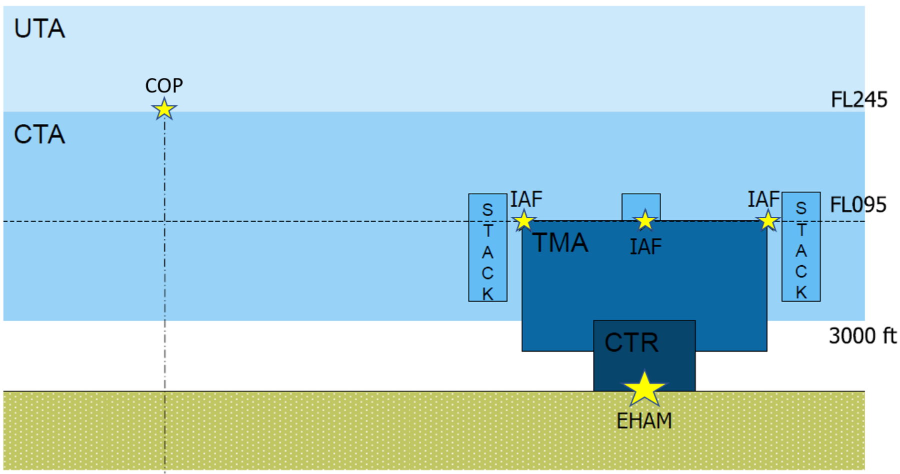


Figure 2.1: Horizontal view of Dutch airspace [J.M. Hoekstra and J. Ellerbroek, 2016b]

As said before, aircraft enter the CTA at the COP. The COP is a navigation point where the control of the aircraft is transferred to/from an adjacent centre. For inbound traffic, an adjacent centre will give control to ACC. ACC will deliver the aircraft over one of the three IAFs: ARTIP, RIVER or SUGOL. At each IAF, a holding stack is located, see also Figure 2.2. This holding stack may be used to absorb delays. Another way of absorbing delays is by using tactical vectors, such as speed or heading instructions. [LVNL, 2016a, D. Ivanescu, A. Marayat and C. Shaw, 2009]

When aircraft enter the TMA, Schiphol APP will guide the aircraft from the IAF towards the runway. There are no fixed routes within the TMA, only best-practices routes. These routes are known by APP and used to guide arriving aircraft efficiently through the TMA. [A. Vanwelsenaere, 2015] Controllers can use directs, vectoring and tromboning to obtain maximum runway throughput [J.M. Hoekstra and J. Ellerbroek, 2016b]. When the aircraft is established on the centerline or the pilots have the runway in sight, the control of the aircraft is transferred to Schiphol TWR. [LVNL, 2016d, D. Ivanescu, A. Marayat and C. Shaw, 2009]

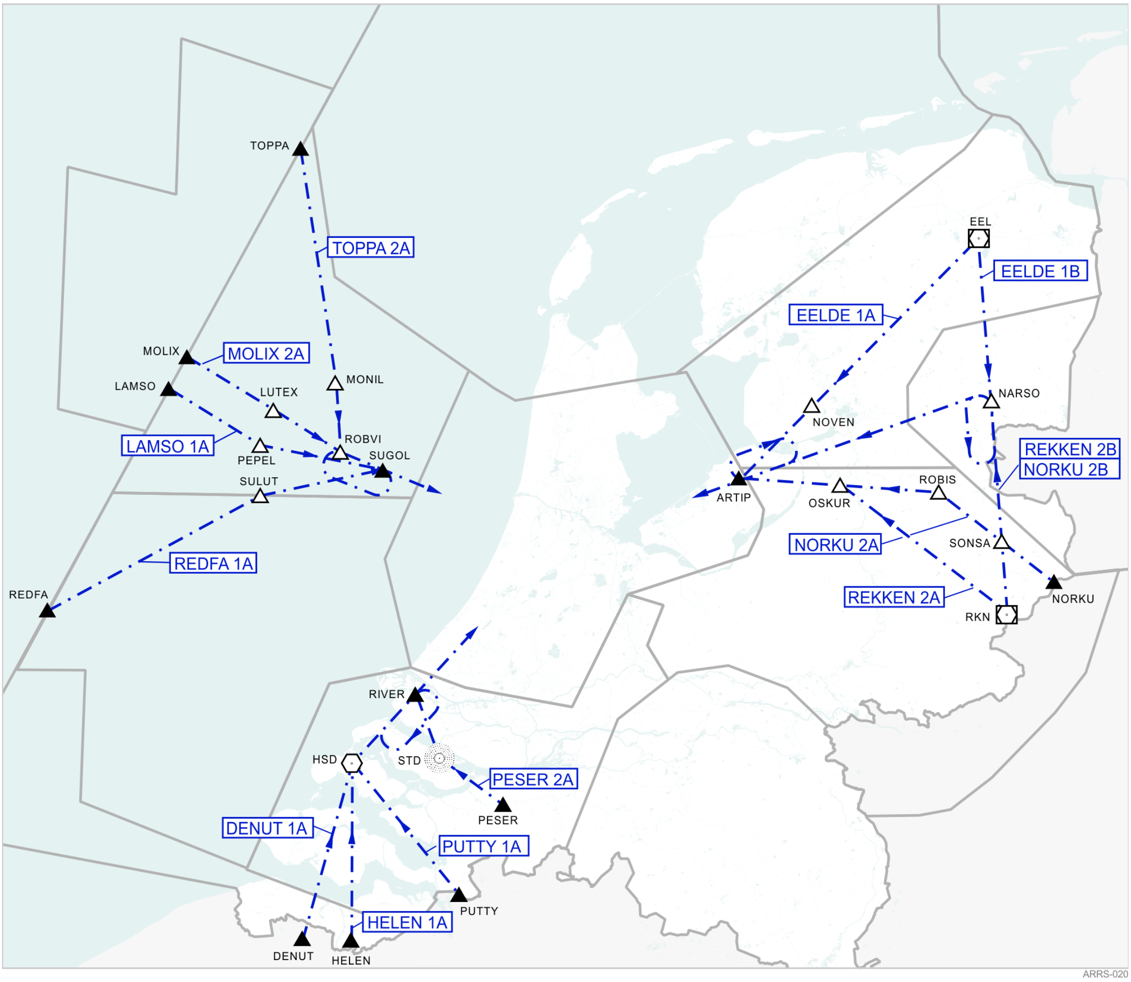


Figure 2.2: Standard Terminal Arrival Routes Schiphol Airport [LVNL, 2016d]

At Schiphol Airport, a minimum of two runways are available at the same time: one runway is used for departures, and one runway is used for landing. During inbound or outbound peaks, more runways can be used by Schiphol TWR to accommodate the traffic. During an inbound peak, two runways are used for landing. Aircraft flying over

IAF ARTIP will generally land on one runway, while the other runway is used by aircraft flying over IAF SUGOL or RIVER. As a result, the traffic streams from SUGOL and RIVER are merged to one runway. By applying dynamic runway reassignment (also, *scharrelen*), the dedicated runway of an aircraft may be changed. *Scharrelen* is to plan a flight and direct it to another runway than is coupled to its IAF [LVNL, 2015a]. Dynamic runway assignment is used in case there is delay on one runway, but available room on the other.

2.3 Arrival Management

Arrival Management (AMAN) is used to safely guide aircraft towards an airport. This section will explain the general AMAN system and will dive into XMAN. Thereafter, the AMAN systems at Schiphol Airport are introduced, including the current working principles.

2.3.1 General Arrival Management

The basis of AMAN is the arrival manager. An arrival manager is and should be used as assistance in the process of arranging arrivals into a flow for landing [N. Hasevoets and P. Conroy, 2010]. The arrival manager consists of four inputs: aircraft performance model, flight plan data, radar data and a weather data model. Based on these inputs, the trajectory prediction module will calculate the Estimated Time of Arrival (ETA) and the Estimated Time Over (ETO), for example, the IAF. The estimated times are fed into the sequencer module. The sequencer module assigns a landing slot, or Scheduled Time of Arrival (STA), to each aircraft and thereby makes a sequence on the basis of a first come, first serve principle. Figure 2.3 graphically depicts the arrival manager.

In AMAN, several horizons are used. A definition of the different horizons is given below:

- Long Range Eligibility Horizon (LREH): The first horizon to cross when aircraft fly towards an airport with XMAN. When the LREH is crossed, the arrival manager receives flight progress information and flight plan information from the aircraft. The trajectory prediction module will start calculating ETAs and a sequence is established. This horizon is an extension of the Eligibility Horizon (EH); [T. Ptz et al., 2015]
- Eligibility Horizon (EH): The first horizon to cross when aircraft fly towards an airport with AMAN. Crossing the EH will also send flight plan and flight progress information from the aircraft to the arrival manager. Based on this information, ETAs are calculated and a sequence is built; [T. Ptz et al., 2015]
- Freeze Horizon (FH): The landing slot time of an aircraft is fixed once the aircraft crosses the FH (also named, plan horizon). The sequence is fixed, and only manual input will change, and hopefully improve, the sequence; [T. Ptz et al., 2015]
- Active Advisory Horizon (AAH): The last horizon is the AAH. When the AAH is crossed, the sequence is presented to the air traffic controller. The sequence is stable and reliable, and the approach slot time is presented. Controllers can start giving advisories to ensure aircraft will adhere to their slot time. The sequence may still be subject to manual changes (e.g. due to pop-up flights). [T. Ptz et al., 2015]

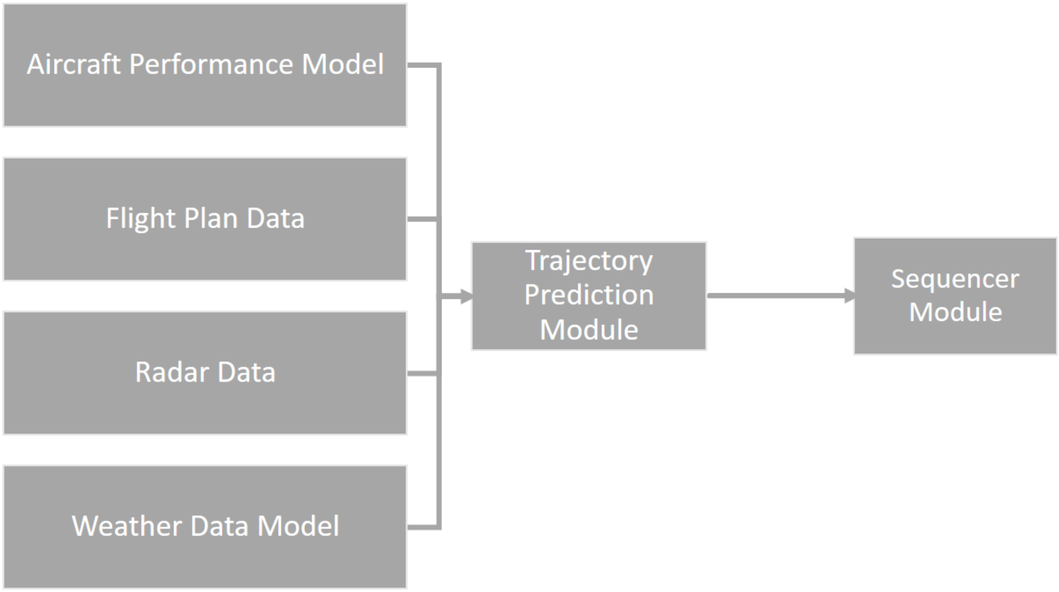


Figure 2.3: The working principles of an arrival manager

2.3.2 Cross-border Arrival Management

XMAN is an extension to AMAN. Typical AMAN horizons are limited up to a maximum of 200 NM, while XMAN extends the horizon up to 500 NM. [M. Tielrooij, C. Borst, M.M. van Paassen and M. Mulder, 2015] However, with an extension of the horizon, three limitations are noticeable: [M. Tielrooij, C. Borst, M.M. van Paassen and M. Mulder, 2015]

1. The availability of information on the predicted arrival time of aircraft;
2. The authority to influence the aircraft;
3. The reliability of the predicted arrival times.

Each of these limitations may be overcome. The first limitation may be overcome by sharing information between ANSPs using, for example, System Wide Information Management (SWIM). SWIM allows sharing of information between and to all airspace users. The second limitation is overcome by having a Letter of Agreement (LoA). A LoA is a written agreement between neighbouring centres on how to deliver and receive aircraft at an airspace border. Most agreements deal with altitude and speed restrictions, and the transfer of control. The third, and last, limitation is assessed during demonstrations. Based on the demonstrations, modifications to the trajectory predictor (TP) may be necessary to improve trajectory prediction and thereby the reliability of the prediction. More information on the TP is found in Section 2.3.3.

As said before, LHR is the first airport to implement the FABEC XMAN concept. Figure 2.4 graphically depicts the XMAN procedure at LHR. In the current situation, aircraft would fly at a fixed Mach speed until reaching the holding stack. All delays would be absorbed in the holding stacks until the aircraft could proceed towards the runway. With the XMAN concept, aircraft that are delayed over ten minutes will receive a Mach reduction of 0.03 at a neighbouring centre. This Mach reduction causes some of the delay to be absorbed en-route, thereby reducing the holding stack time. The reduction in holding stack time caused savings in fuel and CO_2 emissions. Maximum holding delay absorption is in the order of a minute. [T. Ptz et al., 2015, R. Raposo, J. Baker and K. McColl, 2014, NATS, 2016]

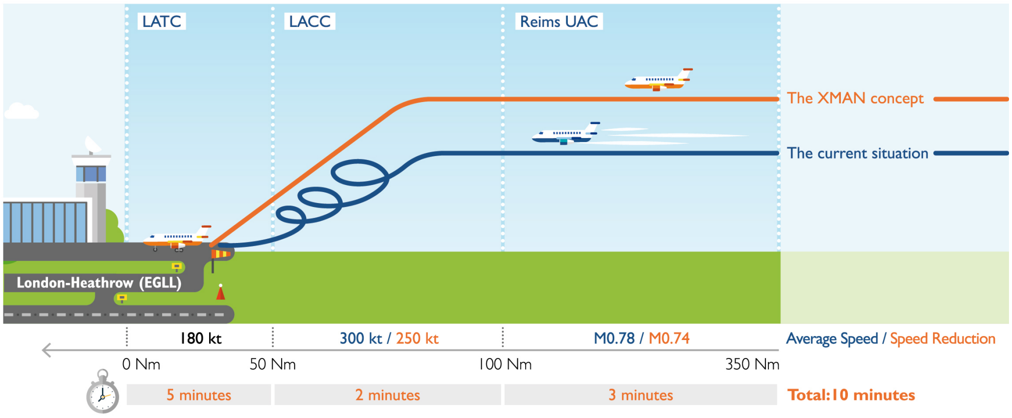


Figure 2.4: Cross-border arrival management for London Heathrow [NATS, 2016]

A drawback to using XMAN is the increase in workload and radio telephony (R/T) for neighbouring centres. The neighbouring centres deemed this increase acceptable. When more airports start using XMAN, the horizons will overlap, as seen in Figure 2.5. For upper centres such as MUAC, the impact of extending the horizon at multiple airports on their operation should therefore be investigated. [T. Ptz et al., 2015, R. Raposo, J. Baker and K. McColl, 2014, NATS, 2016]

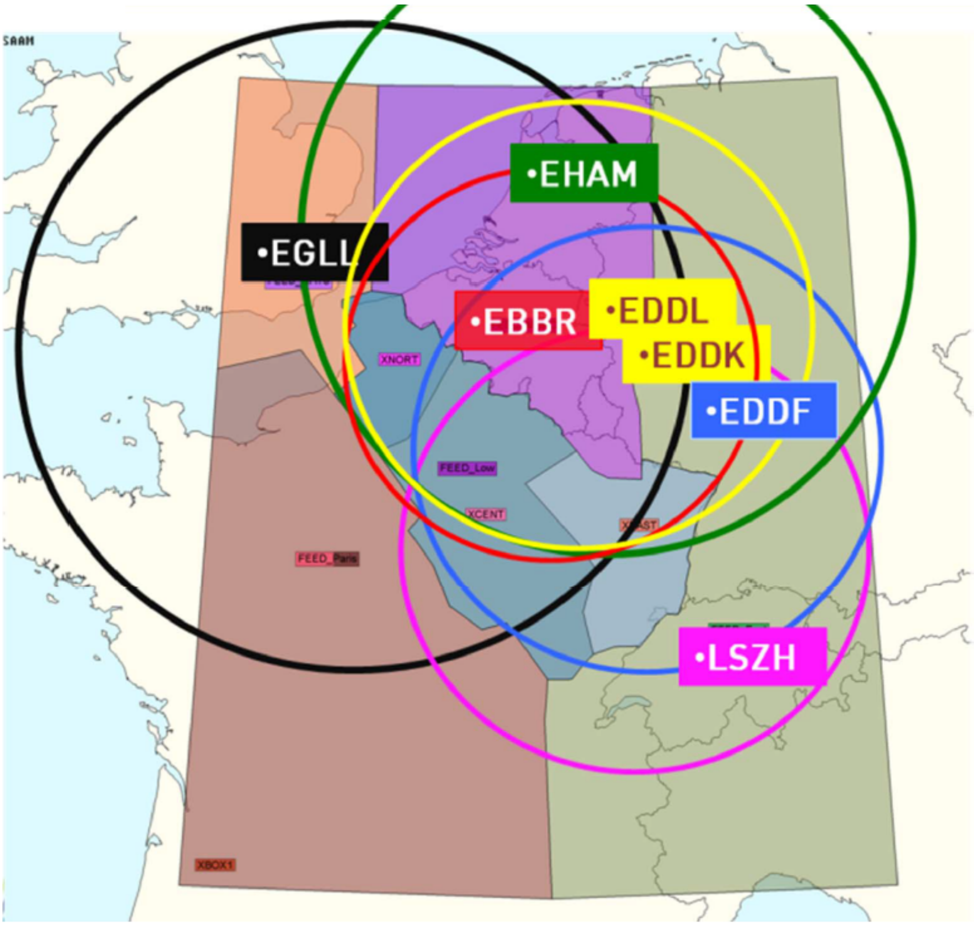


Figure 2.5: Dependencies of cross-border arrival management horizons in Europe [NATS, 2016]

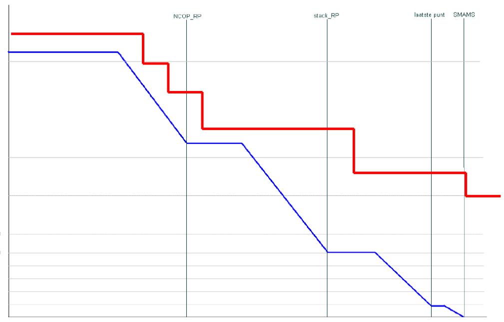
2.3.3 Arrival Management systems at Schiphol Airport

Currently, the Amsterdam Advanced ATC (AAA, read: triple-A) system is in place at Schiphol Airport. The inbound planning system (IBP), part of AAA, is the arrival manager for inbounds to Schiphol Airport. All aircraft flying to one of the three IAFs are subject to the inbound planning. The IBP calculates landing slots, appoints runways, calculates Expected Approach Times (EATs) and calculates any required delays. The TP uses a fixed trajectory of height and speed, as seen in Figure 2.6a, and speed changes are instantaneous. Furthermore, the altitude over the COP is fixed, while in reality the altitude differs per COP. Using AAA, ACC controllers should deliver the aircraft over the IAF within a margin of two minutes. However, there is currently no such a tool to assist ACC in delivering the aircraft within this margin. More information on AAA can be found in the Preliminary Thesis [M. van Horssen, 2017]. [LVNL, 2015a, LVNL, 2016b, LVNL, 2016c]

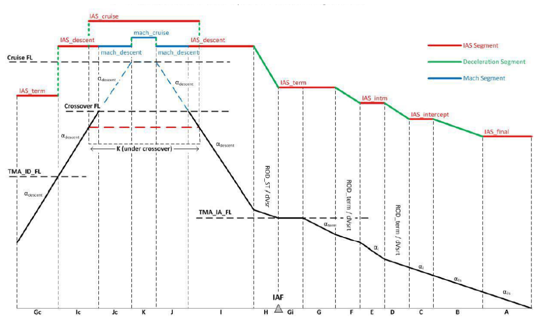
The implementation of the new AMAN system, the Advanced Schiphol Arrival Planner (ASAP), is expected in 2018. The primary objectives for the ASAP are: [LVNL, 2015a]

- to create stable inbound traffic flows in the Schiphol TMA, such that a capacity overload is avoided;
- to use the declared runway capacity to its full extent.

A secondary objective, based on the wants and needs for ACC controllers, is to generate realistic and stable EATs. In order to generate realistic and stable EATs, the TP is improved. The trajectory prediction is improved by, for example, adding deceleration segments instead of using instantaneous speed changes. Next to that, the altitude over the COP is dependent on COP, and the altitude over the IAF is lowered (now: FL 090 instead of FL 100 in AAA). The trajectory prediction profile of the ASAP is seen in Figure 2.6b.



(a) Height (blue) and speed (red) profile of the Trajectory Predictor-Amsterdam Advanced ATC [LVNL, 2015b]



(b) Height (black), Mach speed (blue) and Indicated Airspeed (red) profile of the Trajectory Predictor-Speed And Route Advisor [LVNL, 2015b]

Figure 2.6: Trajectory Predictor profiles for arrival management systems at Schiphol Airport

Another improvement that comes with the ASAP is the introduction of the Speed And Route Advisor (SARA). The SARA should, for traffic inbound to Schiphol Airport, realise a greater accuracy of the planned EATs over the IAFs. In order to introduce fixed arrival routes in the Schiphol TMA, the accuracy of delivery of aircraft over the IAF should increase to thirty seconds instead of the current two minutes. In order to accomplish the thirty seconds margin, the SARA should provide speed or route advisories for each aircraft. With the introduction of the SARA delta t functionality, the delay and ETO the IAF are calculated, and these estimates are updated based on speed input from ACC controllers. If the controller instructs an aircraft to change speed, the SARA delta t functionality will automatically calculate the new ETO the IAF. Using this functionality, ACC controllers will be able to deliver the aircraft over the IAF with greater accuracy.

2.3.4 Working principles

Twenty minutes before aircraft enter the Dutch airspace, flight plan information is sent to the AMAN system. With this information, the ASAP starts to estimate the flying time towards the runway and calculates an ETA. On the basis of the first come, first serve principle, a sequence is established and landings slots are automatically assigned. The sequence is shown to the Approach Planner (APLN), who may update this sequence using front-loading or dynamic runway assignment. Only fourteen minutes before the unconstrained flying time towards the IAF, the sequence is shown to ACC controllers. These controllers are provided with a sequence, together with an EAT and a corresponding delay. The delay is calculated to be the difference between the STA and the ETA. If the delay is greater than the current approach margin of two minutes, ACC controllers should make sure the aircraft absorbs the necessary delay to pass the IAF at the EAT within a margin of two minutes. When the aircraft passes the IAF, it enters the TMA. The control is transferred from ACC to Schiphol APP who will then guide the aircraft towards the dedicated runway. [LVNL, 2015a, LVNL, 2016b, LVNL, 2016c, LVNL, 2016d]

The APLN may update the sequence manually by applying front-loading or dynamic runway reassignment, or by giving landing slots to pop-up flights. Front-loading is to manually plan one or more aircraft ahead of their ETA (as calculated by the ASAP) [M. van Horssen, 2017]. Front-loading will give a negative delay to the involved aircraft. As a result, ACC controllers may use directs or increased speeds to allow the aircraft to arrive as early as possible. Dynamic runway (re)assignment is to manually plan a flight on a different runway than dedicated to its IAF [M. van Horssen, 2017]. Dynamic runway assignment is used when there is too much delay on one runway, but available space and time on the second runway. By changing runways, gaps in the sequence are filled and the sequence presented to ACC controllers will be more stable and reliable. An example of runway reassignment may be seen in Figure 2.7. The yellow dot indicates the landing time on the second runway for MPH082 is 19:34. [LVNL, 2015a]

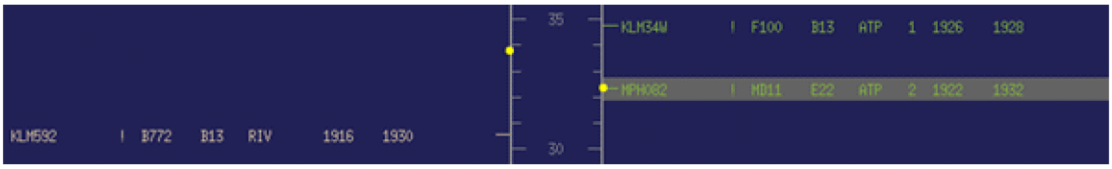


Figure 2.7: Example of runway reassignment [LVNL, 2015a]

2.4 Flow Management

Currently, in order to reduce the traffic demand, regulations are issued to balance the demand and capacity at Schiphol Airport. An explanation of traffic regulations is given at first. Traffic bunching is introduced in the subsequent section, and lastly flight inaccuracy is touched upon.

2.4.1 Traffic regulation

When an over-delivery of aircraft in certain sectors or at airports occurs, it is possible to take Air Traffic Flow & Capacity Management (ATFCM) measures. These measures constrain the number of flights in a limited time frame. By taking these measures, aircraft are grounded and given a later departure time. However, taking an ATFCM measure greatly impacts the capacity and demand balance. Instead of regulating the entire traffic flow, it is also possible to use short-term ATFCM measures (STAMs). A STAM is a local regulation that may influence one up to all flights passing a certain area. More information on STAMs can be found in the Preliminary Thesis [M. van Horssen, 2017].

However, a problem with taking ATFCM measures is shown in Figure 2.8. There is an initial traffic demand that exceeds the capacity at a certain time. A corrective action is taken to smoothen the balance by means of an ATFCM measure or a STAM. As a result, the traffic demand is spread and any peaks are flattened to give a good capacity and demand balance. However, any affected aircraft are still subject to airport and en-route operations. These operations disturb the obtained balance and will cause peaks in the actual traffic received, where some peaks may exceed the capacity. To summarise, the corrective action regulated the flow at first, but due to operations the flow was disturbed again. To solve this problem, corrective actions on en-route traffic seem more appropriate and this is where the concept of XMAN is deemed feasible.

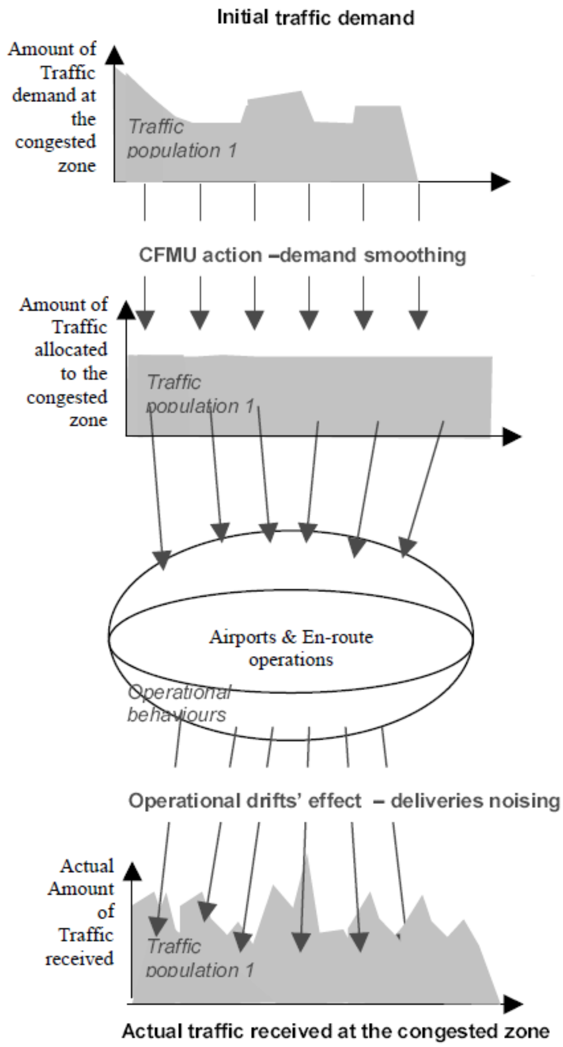
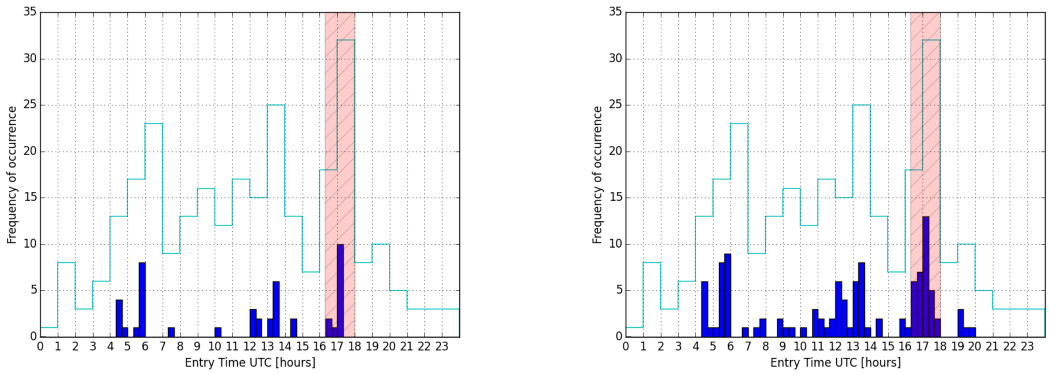


Figure 2.8: Result of Air Traffic Flow & Capacity Management measures on actual traffic [S. Stoltz and P. Ky, 2001]

2.4.2 Traffic bunching

The definition of a traffic bunch, as defined in the Preliminary Thesis, is: *"A second aircraft crossing EHAA CBAS within two minutes of the first aircraft, where the second aircraft got more than two minutes of delay"* [M. van Horssen, 2017]. In this definition, Amsterdam (EHAA) Cross Border Airspace (CBAS) refers to the planning horizon at Schiphol Airport. This definition only takes into account aircraft that are actually delayed, suggesting aircraft that are not delayed will not bunch. The air traffic controller, however, still needs to deal with non-delayed aircraft. Furthermore, including delay in the definition only makes sense for an approach margin of two minutes. When the approach margin is changed, the time difference between two aircraft passing the planning horizon determines whether the aircraft are bunched or not, not the associated delay. The definition will therefore be altered to also include aircraft without delay. Furthermore, the two minutes are based on the current approach margin at Schiphol Airport. In order to investigate a different approach margin, the definition of a traffic bunch should also take into account different margins. The new definition of a traffic bunch will therefore be: *A traffic bunch is defined as a second aircraft crossing the EHAA CBAS within a certain margin of the first aircraft.* This margin can be dependent on the approach margin.

The new definition allows more situations to be analysed. Figure 2.9 graphically depicts the number of traffic bunches per 20 minutes for IAF ARTIP by comparing the old and new definition. For the new definition, a margin of two minutes is used, which is the same margin as is used in the old definition. Figure 2.9a shows the number of traffic bunches using the old definition, while Figure 2.9b shows the number of traffic bunches using the new definition. It is clear the new definition includes more bunches compared to the old definition, as non-delayed aircraft are now included too.



(a) Old definition **(b)** New definition

Figure 2.9: Number of traffic bunches per 20 minutes for Initial Approach Fix ARTIP at Schiphol Airport

2.4.3 Flight inaccuracy

As stated in Section 2.3.2, the third limitation to XMAN is the reliability of the predicted arrival time. Due to the influence of neighbouring air traffic controllers, weather, model inaccuracies and more, the predicted arrival time may not correspond to the actual arrival time. When extending the horizon, it is expected the difference between the predicted and actual arrival time will increase. As a result, a sequence may be built using the wrongly predicted arrival time. To estimate the difference between the predicted and actual arrival time, an analysis is done to find the inaccuracy in flying time towards the IAF with respect to the distance to Schiphol Airport. Using Demand Data Repository (DDR) files [M. Atik, 2016], the difference in flying time between regulated and actual traffic trajectories was determined based on aircraft departing within a given horizon.

By comparing the actual and predicted flying time, the median and average deviation in flying time was found. Table 2.1 shows the results of this comparison: both the median and the average deviation increase with increasing horizon. Or said otherwise, the accuracy of the predicted flying time decreases with increasing horizon. As a result, the ETA may vary substantially for aircraft flying towards Schiphol Airport.

Table 2.1: Analysis on flying time with respect to distance to Schiphol Airport

	Distance to Schiphol Airport [NM]			
Parameter	**<149**	**150-249**	**250-349**	**350-449**
# of Aircraft	88	406	237	346
Median [mm:ss]	01:45	02:03	02:27	02:54
Avg. deviation [mm:ss]	01:11	01:34	01:49	01:55

Based on these results, an uncertainty will be added to the simulation to mimic the unpredictability when extending the horizon. More information on how this uncertainty is added can be found in Section 4.1.

Chapter 3

Research Design

Using the background information, the research can be defined. The research objective and research question are stated, and the experiment variables are noted. Lastly, the hypothesis for the impact of each independent variable on the dependent variables is given.

3.1 Research Objective

The research objective is to perform a feasibility analysis of XMAN at Schiphol Airport. To be more specific, the analysis of XMAN to reduce traffic bunching in Dutch airspace is done by examining the effect of the extension of the horizon and the effect of a tighter approach margin. The research objective is achieved by comparing the simulation of a real air-traffic scenario in the BlueSky ATM Research Simulator with and without the use of XMAN on certain performance parameters, such as workload, total delay and sequence stability. These performance parameters are indicative measures examined to give an indication of the efficiency of the arrival management system. Finally, recommendations are given on the use of XMAN tailored to Schiphol Airport.

3.2 Research Question

An answer to the following research question should be found:

To what extent is traffic bunching influenced by the use of cross-border arrival management at Schiphol Airport?

With the research question, two sub-questions can be identified:

I. What is the effect of the extension of the horizon on the arrival manager performance?

II. What is the effect of the tighter approach margin on the arrival manager performance?

The main research question consists of two keywords: traffic bunching and cross-border arrival management. Traffic bunching is the effect of, at least, two aircraft merging towards a single point, in this research the IAF. The bunches are counted at the planning horizon, in accordance with the definition as given in Section 2.4.2. XMAN has been described in Section 2.3.2; shortly summarising: XMAN involves an extension of the eligibility, active advisory and freeze horizon. This extension should allow pre-sequencing of aircraft. At Schiphol Airport, pre-sequencing is done by making an arrival sequence per IAF. Inside the TMA, the traffic is merged into the final approach sequence for landing, however no tools are used to support the controller with this process. For this research, it is assumed the route and speed information is available once the LREH is crossed. The sequence per IAF is made once the aircraft cross the LREH, and air traffic controllers make sure each aircraft adheres to the sequence after the aircraft has crossed the AAH. Next to that, the approach margin is also altered to determine the effect of XMAN. A tighter margin (± 30 seconds) compared to the current margin (± 120 seconds) can also influence traffic bunching and requires more accurate predictions from the arrival manager. As it is necessary to go to a tighter margin to be able to use fixed arrival routes within the TMA, the impact should be analysed.

Looking at the sub-questions, these questions involve the performance of the arrival manager. When looking at performance, several aspects can be identified: low-level delay absorption, arrival sequence stability, flight plan changes and traffic bunches. Low-level delay absorption will look at the type and amount of delay absorption. Arrival sequence stability includes the number of sequence revisions, number of STA revisions and the delivery accuracy over the IAF.

Flight plan changes can be divided into disturbed descents and number of speed changes. Any (un)disturbed descents show how efficient the pilot can make the descent towards the IAF. The number of speed changes en-route and during descent can also be monitored. The number of speed changes en-route will show how often a neighbouring centre should give an instruction to a pilot to improve the arrival process for Schiphol Airport. The number of speed changes during descent indicate the additional instructions issued by the air traffic controllers in the Netherlands. Based on the flight plan changes and number of traffic bunches, a recommendation can be given on how XMAN influences the pilot's and air traffic controllers' work.

3.3 Experiment Variables

As with every research, there are three types of variables: controlled, independent or dependent variables. The coming sections will elaborate on each of the variables specific to the simulation.

3.3.1 Independent Variables

This research investigates the effect of traffic bunching by varying the type of arrival manager and the approach margin. Two types of arrival manager are used: AMAN and

XMAN, and also two approach margins are used: 30 seconds and 120 seconds.

3.3.2 Dependent Variables

The effect of the extension of the horizon on the arrival manager performance is uncertain. Extending the horizon leads to a higher inaccuracy in predicted flying time, as was analysed in Section 2.4.3. However, a sequence can be built earlier in time, which has the advantage of less controller input and less low-level delays. Next to that, the increase in pop-up flights will most likely cause a negative effect on the performance. At this stage, it is unknown whether the inaccuracy will prevail over the advantages of an earlier sequence. It is however expected the number of traffic bunches, as counted at the CBAS horizon, should reduce, as aircraft should arrive more spread out.

The effect of the tighter approach margin on the arrival manager performance is also uncertain, since there are both pros and cons. Advantages of a tighter margin are a more stable sequence (the approach margin of two EATs do not overlap, see Figure 3.1), more en-route delay absorption and a higher predictability of traffic as the delivery accuracy will increase. Disadvantages are more low-level delay absorption, more (intense) speed changes for the pilot and a higher delay per flight. The number of traffic bunches, as counted at the CBAS horizon, should reduce too as tighter margins will require aircraft to be more on time.

3.3.3 Controlled Variables

To ensure the effect of the dependent variables is dependent on the change in independent variables, several variables need to be controlled. The actual trajectories, using DDR *SO6 m3* files, are used to ensure all aircraft fly realistic routes towards the IAF. Only inbound traffic to Schiphol Airport is simulated. The interaction between inbound traffic and other traffic is left out of the simulation mainly to reduce computational loads. Next to that, conflict detection and resolution is not used. Due to the simulation set-up, conflict free entry into the TMA is ensured. The routes may, however, not be conflict free. In reality, an air traffic controller will make sure there is enough lateral and vertical separation between aircraft. It is assumed the effect of conflict detection and resolution on the actual trajectories is minimal, and is therefore left out of the simulation.

A single aircraft performance model is used, the B747-400. Using a single model, it is assured every aircraft will respond in the same way to en-route speed changes, and the maximum and minimum speed of each aircraft is the same. The type of aircraft will therefore not influence the results. As will be explained in Section 4.1, a speed offset and speed offset deviation is used for each aircraft to increase the inaccuracy in flying time. The speed offset and speed offset deviation bundles inaccuracies due to, for example, the influence of neighbouring air traffic controllers, weather, model inaccuracies and airline intent.

Furthermore, a fixed arrival route between the IAF and the pre-determined runway is used. Next to that, time-based sequence separation at the runway is used instead of distance-based separation. Time-based sequence separation simplifies the operations within the

TMA. As TMA operations are not of importance for this research, these assumptions should not influence the results up to the IAF.

3.4 Hypothesis

By changing the type of arrival manager to XMAN, it is hypothesised the amount of low-level delay will decrease (H1-1) as more delay is absorbed en-route. The number of STA revisions and number of sequence changes may either increase due to the trajectory prediction inaccuracy, or decrease due to the fact that a sequence can be made earlier in time. It is expected the number of sequence changes (H1-2) and number of STA revisions (H1-3) will decrease as the availability of a sequence earlier in time will outweigh the effects of trajectory prediction inaccuracy. The accuracy of aircraft over the IAF should not be affected by using XMAN (H1-4) as the air traffic controller will assure each aircraft will pass the IAF at their EAT within the approach margin. Next to that, there should be no effect on the runway inter-arrival time (H1-5) as TMA operations should not be affected by the XMAN procedure. The number of disturbed descents should reduce as delay is absorbed en-route (H1-6), while the number of speed changes should increase (H1-7) as the delay is absorbed by speed reduction. Last but not least, the number of traffic bunches will reduce as aircraft arrive more spread out (H1-8).

When the approach margin is tightened, it is hypothesised the amount of low-level delay will increase (H2-1) as aircraft need to absorb more delay to be able to pass the IAF within the approach margin. The number of sequence changes (H2-2) and STA revisions (H2-3) will decrease as the approach margin will not overlap (see Figure 3.1). The delivery accuracy will increase (H2-4) as the predictability of aircraft is higher. Looking at inter-arrival time, it is expected no difference is seen (H2-5) as TMA operations are not affected. The number of disturbed descents is expected to increase (H2-6) as more delays should be absorbed prior to entering the TMA. The number of speed changes will increase (H2-7) as aircraft are required to absorb delays at an earlier stage and, most likely, more delay should be absorbed. Lastly, the number of traffic bunches are expected to reduce (H2-8) as aircraft arrive on a tighter schedule, thereby increasing the distance between two aircraft.

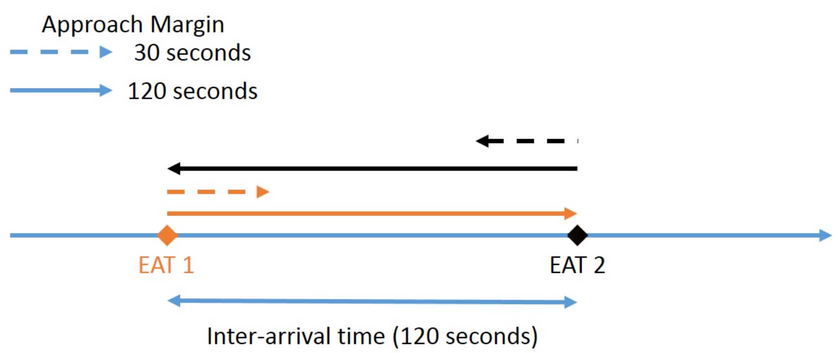


Figure 3.1: Approach margin overlap for two aircraft based on expected approach time

Chapter 4

Simulation Set-Up

With the designed research, a simulation set-up can be made. At first, an explanation of the speed offset is given. Thereafter, the two scenarios are stated. The sample size is given in the penultimate section and lastly the AMAN Research Simulator (ARSIM) is explained.

4.1 Speed offset

Based on the results in Section 2.4.3, an uncertainty should be added to the simulation to mimic the inaccuracy at a larger horizon. A speed offset and a speed offset average deviation can be calculated to add the uncertainty in flying time into the simulation. When using AMAN, the speed offset and speed offset average deviation are assumed to be zero. The assumption is made that the trajectories and the flying time within the Dutch airspace are calculated accurately. The instructions of the air traffic controller will cause an automatic recalculation of the ETO the IAF, just like SARA delta t would do. The estimated flying time thereby corresponds to the actual flying time. Outside the Dutch airspace, the trajectories are estimations, since the flying time of each aircraft is subject to, for example, weather, aircrew intent and neighbouring air traffic controller instructions. By applying a speed offset and a speed offset average deviation, there is a mismatch between the input trajectory data for the TP and the actual flight trajectory. This mismatch will cause an estimate that is not fully correct and thereby mimic the uncertainty in flying time.

Using a cruise speed of 510 kts True Airspeed (TAS), which is the cruise speed of a B747-400 used by the AAA TP [A. Vanwelsenaere, 2016], the average flying time was calculated. By adding the median to the average flying time, the speed offset was calculated per horizon. A negative speed offset means an increase in flying time. Next to that, by adding and subtracting the average deviation to the average flying time, a speed offset average deviation was calculated per horizon. The results are shown in Table 4.1. These values will be used during each of the scenarios.

Table 4.1: Speed offset and speed offset average deviation as a function of horizon

Parameter	XMAN Horizon 250 [NM]	350 [NM]	450 [NM]
Speed offset [kts]	-33	-28	-26
Speed offset dev. [kts]	±27	±22	±18

4.2 Scenarios

Based on the independent variables, several scenarios are made to get the best results to answer the sub-questions. Since there are two independent variables, two scenarios will be used for analysis. The first scenario, as depicted in Table 4.2, will show the effect of a horizon extension on the arrival manager. At first, an arrival manager AMAN with planning horizon 120 NM will be used, which resembles the current planning horizon at Schiphol Airport. Subsequently, an arrival manager XMAN with different planning horizons is used. The smallest XMAN horizon, 250 NM, is the horizon up to and including the airspace of Maastricht UAC. This horizon may be used when real-life trials are initiated. 350 NM is the airspace of Maastricht UAC up to and including Rhein UAC (in Eastern direction) or Reims UAC (in Southern direction). Both Maastricht UAC and Reims UAC are already involved in the LHR XMAN concept, and it should be a small step to involve them in the Schiphol Airport XMAN concept too. 450 NM is used to show the working principles of a long-range XMAN, but does not suit real-life purpose (yet) due to the lack of interoperability between all involved air traffic control systems. In all four sub-scenarios, the arrival airport is Schiphol Airport with an approach margin of ± 30 seconds.

Table 4.2: Scenario I: Effect of horizon extension on arrival manager

Parameter	Scenario i	ii	iii	iv
Type	AMAN	XMAN	XMAN	XMAN
Planning Horizon [NM]	120	250	350	450
Speed offset [kts]	0	-33	-28	-26
Speed offset dev. [kts]	0	27	22	18
Approach margin [sec]	30			
Arrival Airport	Schiphol Airport			

For the remainder of the report, the following terminology will be used:

- AMAN: AMAN with horizon of 120 NM (scenario i).
- XMAN250: XMAN with horizon of 250 NM (scenario ii).
- XMAN350: XMAN with horizon of 350 NM (scenario iii).
- XMAN450: XMAN with horizon of 450 NM (scenario iv).

The second scenario, shown in Table 4.3, will show the effect of the approach margin on the arrival manager. Again four sub-scenarios are used, where the first scenario is equivalent to the real AMAN operational at Schiphol Airport. With an approach margin of ± 120 seconds and a planning horizon of 120 NM, the arrival manager closely resembles the current AMAN system. Due to the requirement on the approach margin of ± 30 seconds to be able to apply fixed arrival routes within the TMA, an approach margin of ± 30 seconds is needed, as seen in the second scenario. Scenario iii and iv use XMAN as the arrival manager with ± 120 seconds and ± 30 seconds approach margin, respectively. Both XMAN scenarios have a planning horizon of 350 NM. This planning horizon will allow the involvement of both Maastricht UAC and Reims UAC in the XMAN concept for Schiphol Airport. For all scenarios, the arrival airport is Schiphol Airport.

Table 4.3: Scenario II: Effect of approach margin on arrival manager

Parameter	Scenario i	Scenario ii	Scenario iii	Scenario iv
Type	AMAN	AMAN	XMAN	XMAN
Approach margin [sec]	120	30	120	30
Planning Horizon [NM]	120	120	350	350
Speed offset [kts]	0	0	-28	-28
Speed offset dev. [kts]	0	0	22	22
Arrival Airport	Schiphol Airport			

For the remainder of the report, the following terminology will be used:

- A-M120: AMAN with approach margin of 120 seconds (scenario i).
- A-M30: AMAN with approach margin of 30 seconds (scenario ii).
- X-M120: XMAN with approach margin of 120 seconds (scenario iii).
- X-M30: XMAN with approach margin of 30 seconds (scenario iv).

4.3 Sample Size

Several samples have been used to simulate flights for each of the scenarios. Table 4.4 shows the number of flights per traffic sample. These samples were taken from the DDR of Eurocontrol [M. Atik, 2016] and represent a three hour inbound peak to Schiphol Airport. The inbound peaks between 04:00 Universal Coordinated Time (UTC) and 07:00 UTC, and between 16:00 UTC and 19:00 UTC are simulated.

Table 4.4: Sample Size

Sample	# Aircraft	Sample	# Aircraft	Sample	# Aircraft
1	122	5	123	9	124
2	142	6	145	10	140
3	124	7	125	11	136
4	138	8	143	12	136

4.4 AMAN Research Simulator

The experiments are run using the BlueSky ATM Research Simulator (from hereon: BlueSky), an open-source, open-data Air Traffic Management (ATM) simulator. [J.M. Hoekstra and J. Ellerbroek, 2016a] BlueSky, see Figure 4.1, consists of several modules. Modules deemed important for this research are: *Sim*, *Stack* and *Traf*. *Sim* manages the simulation and calls other modules to perform their tasks. *Stack* allows the processing of commands using the command window, or using a scenario file. Lastly, *Traf* contains the module of the ARSIM and calculates the route and flight plan of each aircraft. The main file within *Traf* is *traffic.py*, which processes the information on each simulated aircraft, such as flight plan and performance data. Flights can be created or deleted, but are also managed. Each aircraft can fly using Lateral Navigation (LNAV) and Vertical Navigation (VNAV) capabilities, or using speed, heading and altitude commands. In both cases, the aircraft fly on a simulated auto-pilot. A more detailed description of BlueSky can be found in the Preliminary Thesis [M. van Horssen, 2017].

Figure 4.1: BlueSky ATM Research Simulator

A recent development within BlueSky is ARSIM. ARSIM was developed to examine the effect of pop-up flights on the (extended) arrival manager. [A. Vanwelsenaere, 2016] However, ARSIM was developed in such a way that several research topics on the (extended) arrival manager can be performed, including this research. The basic principles of ARSIM are based on the working principles of ASAP. More information is presented in the coming sections.

4.4.1 Working Principles

As said before, ARSIM operates within the *Traf* module. Figure 4.2 shows the interconnection between the two classes. Whenever an update is initiated, the callsign, position, current speed and active waypoint of each aircraft are used by the ARSIM class. Based on these inputs, the TP estimates the trajectory and determines the flying time towards the runway. Based on the ETA, the scheduler makes a sequence based on the basis of the first come, first service principle. Each aircraft obtains an STA and EAT, and delay is calculated. When the delay is more than the approach margin, aircraft should absorb delays prior to entering the TMA. Speed advisories are issued during cruise to ensure the aircraft absorb delays prior to reaching waypoint almost-IAF. When the aircraft reach waypoint almost-IAF, route advisories may be issued if the delay is still higher than the approach margin. These speed and route advisories are processed in the *traf* class to ensure the aircraft flies according to the new advisories.

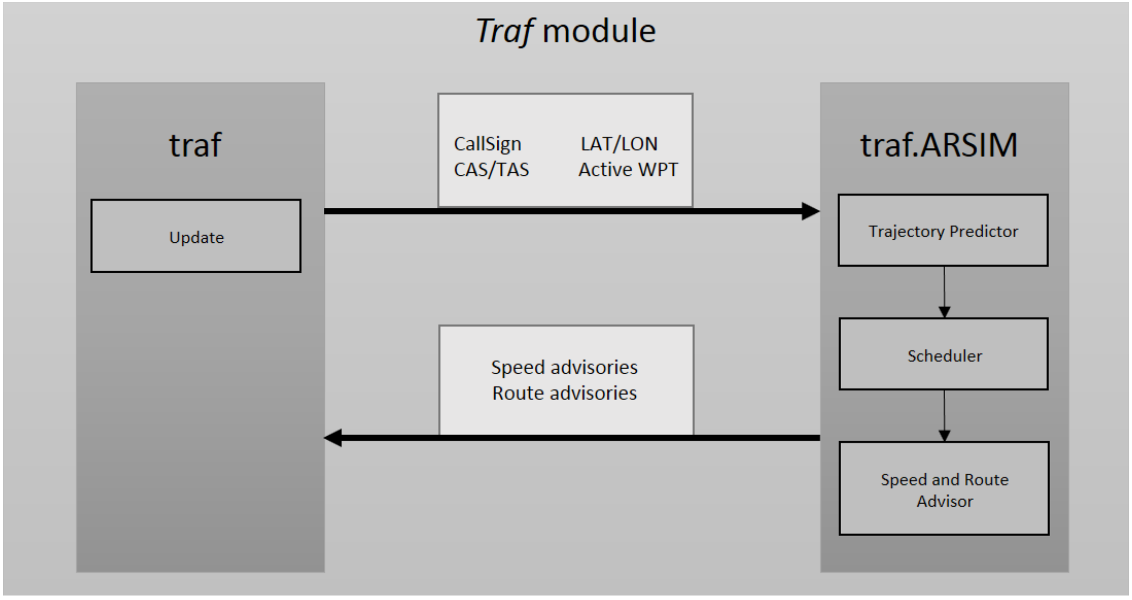


Figure 4.2: BlueSky *Traf* module

A speed offset, as calculated in Section 4.1, is implemented as an inaccuracy in TAS. To the current TAS, a speed offset and speed offset deviation are added. As a result, the TAS used by the TP is different from the TAS as flown by the aircraft. Or to state it differently, the aircraft behaves differently compared to the estimations by the TP. This difference will cause a mismatch between the aircraft's behaviour and its intentions, simulating the effect of uncertainty at a greater distance. The speed offset and speed offset deviation are added when the aircraft cross the EH. Up until 120 NM (i.e. outside the AMAN horizon), the inaccuracy is added to the current TAS. After 120 NM, the data is considered accurate, and the speed offset and speed offset deviation are removed.

When aircraft cross the EH, the status of the aircraft is considered variable. Flight plan information is taken into account, an ETA is calculated, and the scheduler makes a sequence. The aircraft obtains a variable STA, meaning the STA is still subject to changes. The STA is calculated according to Equations (4.1) to (4.3), where the landing interval (LIV) is a fixed interval. Equation (4.1) states the first possible STA is the ETA of the aircraft. Equation (4.2) states the second possible STA is the STA of the previous aircraft plus the LIV. Lastly, Equation (4.3) states the actual STA is the maximum of the two possible STAs.

$$STA_{(i,1)} = ETA_{(i,1)} \tag{4.1}$$
$$STA_{(i,2)} = STA_{(i-1)} + LIV \tag{4.2}$$
$$STA_i = max(STA_{(i,1)}, STA_{(i,2)}) \tag{4.3}$$

When the aircraft crosses the FH, the status of the aircraft changes to semi-fixed. The STA will also become semi-fixed, meaning the slot can only change when a revision is unavoidable (e.g. due to a pop-up flight). Soon after the FH, the aircraft will cross the AAH meaning air traffic controllers may start giving advisories to ensure all aircraft adhere to their EAT. ACC controllers should ensure each aircraft passes the IAF at their EAT within the approach margin. During the en-route phase of flight, the aircraft are given speed advisories to absorb any delay. For simulation purposes, speed advisories given prior to Top Of Descent (TOD) are assumed to have been given by neighbouring control centres. Speed advisories after TOD are assumed to be given by Amsterdam ACC. Speed advisories are given up until waypoint almost-IAF. Any advisories prior to waypoint almost-IAF will show the impact of using speed reduction on delay absorption. If the delay is still too high (i.e. outside the approach margin) when reaching almost-IAF, route advisories are issued to absorb the remaining delay. These route advisories are also referred to as final delay absorption strategy. Once aircraft enter the TMA, a fixed route will be flown towards the runway. No delay absorption is possible inside the TMA.

4.4.2 Scenario Generator

The scenario generator initialises the simulation according to the user's input. The user can specify, for example, a traffic sample, type of arrival management and the corresponding horizons, inter-arrival time, approach margin and pop-up ratio. Based on these inputs, the scenario file and the simulation are accustomed to the user. The traffic sample, a DDR file from Eurocontrol [M. Atik, 2016], will be used to initialise the flights and the corresponding routes. The routes are split between outside TMA route and inside TMA route. As said before, the inside TMA route is a fixed route from the IAF to the runway. The outside TMA route is the route from departure airport up until the IAF. The waypoint almost-IAF is added on the route 15 NM prior to the IAF. This waypoint will be used to determine a final delay absorption strategy.

Flights can also be modified based on the flight distance. Since arrival management only takes place starting at a maximum of 450 NM, simulating long haul flights is unnecessary, as only the last two hours of the flight are important for the simulation. As a result, long haul flights may be replaced by shorter flights. The ETA will be the same, however less computational resources are necessary and simulation time is shortened.

A more detailed explanation on the outside and inside TMA route can be found in the Preliminary Thesis [M. van Horssen, 2017].

4.4.3 Speed and Route Advisor

The SARA will give speed and route advisories based on the delay of the aircraft. Delay is defined as the difference in time between the STA and the ETA, as seen in Equation (4.4).

$$Delay \quad = \quad Scheduled\,Time\,of\;Arrival - Estimated\,Time\,of\;Arrival \qquad (4.4)$$

When the delay is still within the approach margin, the aircraft may continue as planned. However, when the delay is outside the approach margin, the air traffic controller should give an instruction to ensure the aircraft passes the IAF at its EAT within the approach margin. In the simulation, a so-called speed delay ratio (SDR) is calculated as shown in Equation (4.5).

$$SDR = \frac{Delay\,to\,be\,absorbed \pm approach\,margin}{Maximum\,delay\,absorption\,possible\,by\,speed\,reduction} \qquad (4.5)$$

The delay can both be positive and negative. A positive delay means the aircraft is estimated to arrive earlier than its STA. The speed may be reduced to reduce this delay. A negative delay means the aircraft is estimated to arrive later than its STA, meaning the aircraft should accelerate. During the simulation, the aircraft may not accelerate beyond its nominal speed, while a maximum speed reduction of 10% is possible. [A. Vanwelsenaere, 2016] If the SDR is between 0 and 1, the aircraft's speed is reduced with the same ratio as calculated by the SDR. An SDR of 1 indicates the aircraft's speed is fully reduced. If the SDR increases beyond 1, the aircraft's speed is still fully reduced, however some of the delay cannot be absorbed using speed reduction only.

Any delay that cannot be absorbed by speed changes will be absorbed in the last 15 NM prior to passing the IAF. When waypoint almost-IAF is reached, a final delay absorption strategy is chosen based on the remaining delay. Three strategies are possible: a dogleg, two semicircles leg and a variable holding pattern. [A. Vanwelsenaere, 2016, M. van Horssen, 2017]

The first vectoring strategy is a dogleg, see Figure 4.3. A dogleg is a waypoint added in parallel to a route to increase the distance to be flown, thereby increasing the flight time. The required airspace to fly a dogleg increases with delay. To minimise the required airspace, doglegs are only flown if the delay is between 30 and 50 seconds for aircraft flying to IAF ARTIP or SUGOL. For aircraft flying to IAF RIVER, up to 150 seconds of delay may be absorbed using a dogleg. [A. Vanwelsenaere, 2016, M. van Horssen, 2017]

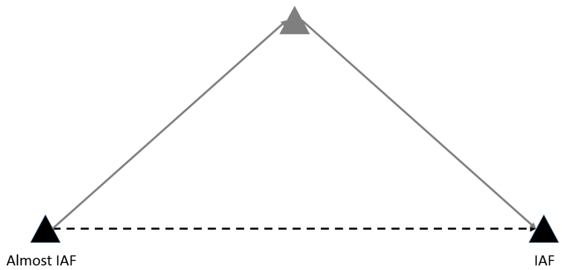


Figure 4.3: A dogleg

The second vectoring strategy is a two semicircles leg. Several waypoints are added to make the aircraft fly two semicircles between almost-IAF and IAF, as shown in Figure 4.4. A two semicircles leg is flown when the delay exceeds 50 seconds, but stays below 150 seconds for aircraft flying to IAF ARTIP or SUGOL. For IAF RIVER, a dogleg may be flown up to 150 seconds of delay, meaning a two semicircles leg is not needed. [A. Vanwelsenaere, 2016, M. van Horssen, 2017]

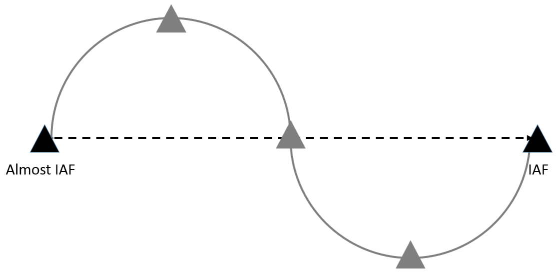


Figure 4.4: Two semicircles leg

Lastly, a variable holding pattern is used when delays are greater than 150 seconds. An example of such a holding pattern is seen in Figure 4.5. A variable holding pattern up to 300 seconds may be flown. If more than 300 seconds of delay should be absorbed (for example, 400 seconds), two identical holdings patterns (of 200 seconds) are made. The variable holding pattern can be flown at any IAF. [A. Vanwelsenaere, 2016, M. van Horssen, 2017]

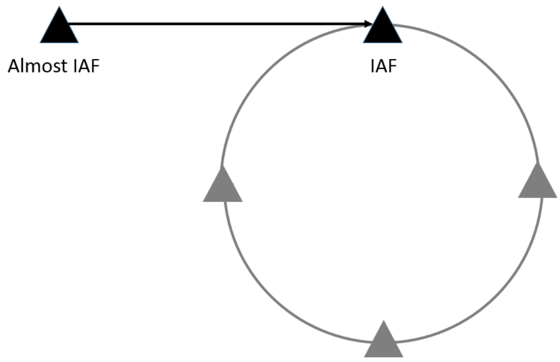


Figure 4.5: A variable holding pattern

Chapter 5

Results

This chapter presents the results of the two scenarios. Statistical analyses were carried out using normalised and standardised Z-scores. The magnitude of each effect was analysed using the average of the results. Shapiro-Wilk tests indicated the majority of Z-scores were not normally distributed. Therefore, only non-parametric tests were considered for statistical analysis using Friedman's ANOVA test to test for a significant effect. Effects were considered significant for $p \leq 0.05$. Post-hoc tests were performed using a Wilcoxon's Signed Rank test to compare the data between multiple pairs, as the data is not normally distributed. The coming two sections show the results for each scenario.

5.1 Scenario I: Extension of Horizon

The first scenario looked at the extension of the horizon and the performance on the arrival manager. In this section, the following terminology will be used as defined in Section 4.2:

- AMAN: AMAN with horizon of 120 NM (Scenario I-i).
- XMAN250: XMAN with horizon of 250 NM (Scenario I-ii).
- XMAN350: XMAN with horizon of 350 NM (Scenario I-iii).
- XMAN450: XMAN with horizon of 450 NM (Scenario I-iv).

Four pairs were investigated in the post-hoc test: AMAN – XMAN250, AMAN – XMAN350, AMAN – XMAN450 and XMAN250 – XMAN350. With these four pairs, a Bonferroni correction of four is used to reduce the Type I error. A Type I error is the error of observing a statistical difference, while in fact there is no difference. Post-hoc tests were, using the Bonferroni correction, considered significant when $p \leq 0.0125$.

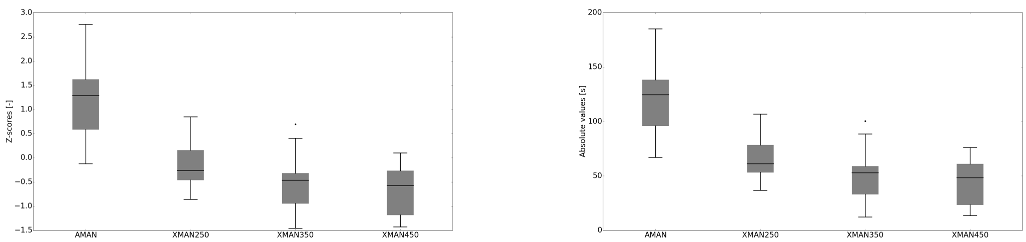
5.1.1 Low-level delay absorption

Low-level delay indicates the amount of delay that should still be absorbed prior to entering the TMA at the EAT within the approach margin. Delay absorption using only speed-control was possible until waypoint almost-IAF (last waypoint 15 NM before the IAF), after which a low-level delay absorption strategy was chosen dependent on the remaining amount of delay. To shortly summarise what has been presented in Section 4.4.3, doglegs and semicircles were flown for relatively small delays (up to 150 seconds), while holdings (also called stacks) were flown for delays greater than 150 seconds. Table 5.1 indicates, on average, how much delay was absorbed at a low-level, how many aircraft were subject to a certain strategy and the amount of delay absorbed per strategy.

Table 5.1: Scenario I: Low-level delay absorption

Parameter	AMAN	XMAN250	XMAN350	XMAN450
Low-level delay [s]	124.3	67.6	51.7	44.5
# of doglegs [-]	17	9	7	8
Time in doglegs [s]	64.3	59.1	67.9	65.4
# of semicircles [-]	19	10	9	9
Time in semicircles [s]	95.5	93.5	91.4	93.4
# of stacks [-]	40	24	19	17
Time in stacks [s]	339.0	311.3	285.0	267.7

The results in Table 5.1 show the average low-level delay decreases with an extension of the horizon. The number of doglegs, semicircles and stacks indicates the average number of aircraft subject to each strategy. In all cases, the number of aircraft decreases. The time in doglegs, semicircles or stacks indicate the average time an aircraft spent flying a certain strategy. The time spent in doglegs at first slightly drops to below 60 seconds for XMAN250, but thereafter increases again to over 65 seconds. The time spent in semicircles fluctuates around 93 seconds. The time spent in stacks actually decreases with an extension of the horizon.



(a) Z-score

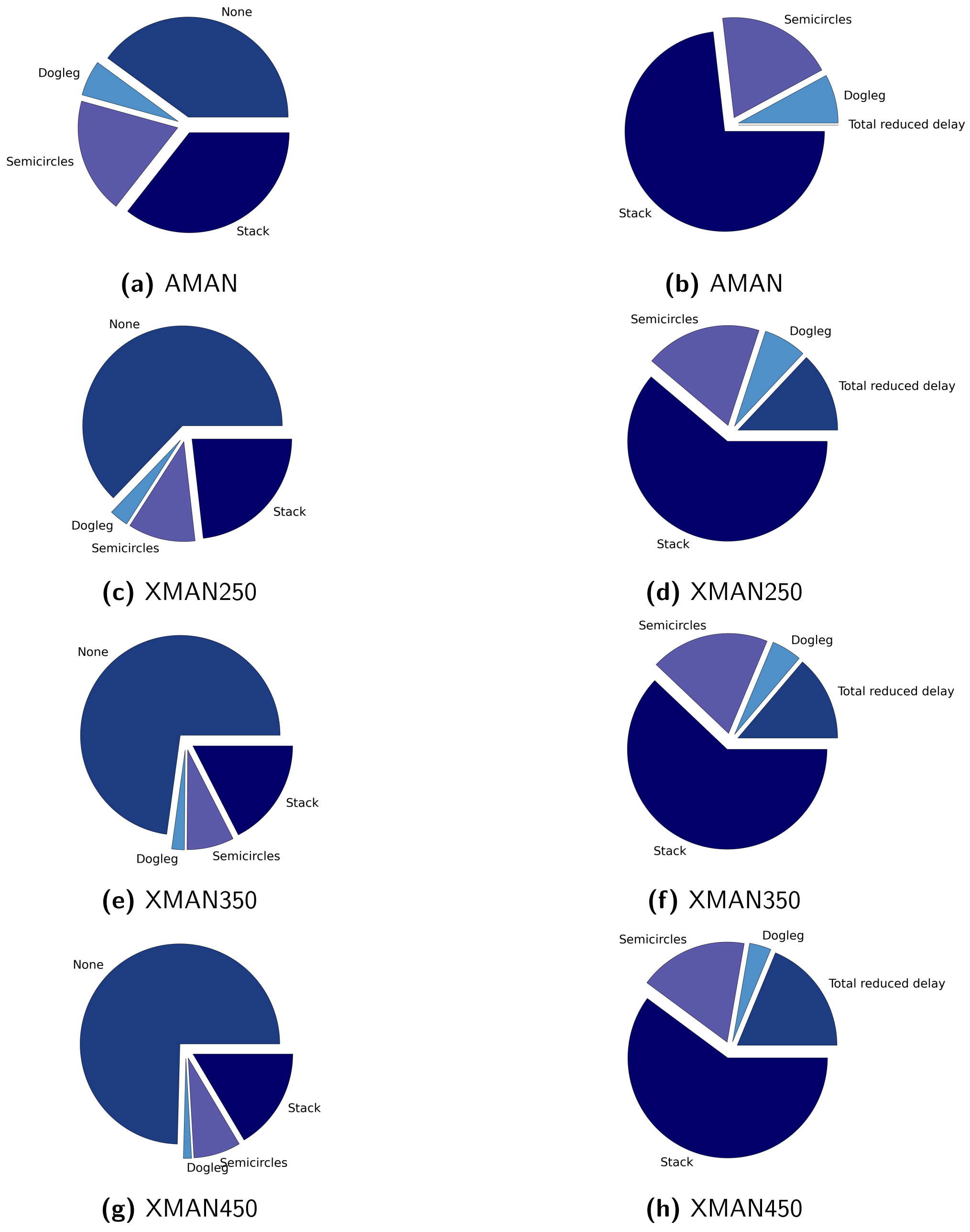
(b) Absolute value

Figure 5.1: Boxplots Scenario I: Low-level delay absorption – low-level delay

Figure 5.1 shows the boxplots for low-level delay absorption. A main effects test showed a significant effect in low-level delay absorption ($\chi^2(3) = 34.0, p \leq 0.05$). Post-hoc tests revealed a significant effect ($p \leq 0.0125$) for all horizons compared to the AMAN condition. Furthermore, a significant difference is seen in low-level delay between XMAN250 and XMAN350 ($p \leq 0.0125$). As a result, an increase in horizon will cause a reduction in low-level delay, at least up to 350 NM.

IAF ARTIP

In order to look at the type of low-level delay, the data was split up for each IAF. Figure 5.2 shows the low-level delay absorption strategy for IAF ARTIP, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson Chi-Square test is used to test significance on categorical variables, where results are considered significant for $p \leq 0.05$.



(a) AMAN **(b)** AMAN
(c) XMAN250 **(d)** XMAN250
(e) XMAN350 **(f)** XMAN350
(g) XMAN450 **(h)** XMAN450

Figure 5.2: Scenario I: Low-level delay absorption strategy for Initial Approach Fix ARTIP. Left: number of aircraft; right: amount of delay

The Pearson Chi-Square test indicated a significant result for aircraft without low-level delay ($\chi^2(75) = 96.80, p \leq 0.05$). Looking at Figures 5.2a, 5.2c, 5.2e and 5.2g, the number of aircraft without delay indeed increases when extending the horizon. For AMAN, about 35% of the aircraft do not have to absorb delays, while for XMAN450 almost 75% of all aircraft do not have to absorb delays.

Looking at the number of aircraft subject to a dogleg, the Pearson Chi-Square test showed a significant result ($\chi^2(18) = 32.19, p \leq 0.05$). The number of aircraft subject to a dogleg decreases when extending the horizon. When looking at the time spent flying a dogleg, the Pearson Chi-Square test indicated no significance ($\chi^2(111) = 119.27, p = 0.28$). There seems to be a tendency of a reduction in time spent flying a dogleg when extending the horizon, but this tendency is not significant.

The Pearson Chi-Square test revealed no significant results when looking at the number of aircraft flying semicircles ($\chi^2(51) = 59.05, p = 0.21$). Also the time spent flying semicircles was not found to be significant when applying the Pearson Chi-Square test ($\chi^2(141) = 114.0, p = 0.41$). The number of aircraft flying semicircles tends to decrease from AMAN to XMAN250, but appears to stay constant when extending the horizon beyond 250 NM. The time spent flying semicircles also appeared to stay constant throughout the extension of the horizon.

Lastly, according to the Pearson Chi-Square test, the number of aircraft subject to a stack could not be found significant ($\chi^2(69) = 66.33, p = 0.57$). The number of aircraft however tends to reduce from AMAN to XMAN350, but no more reduction can be seen after 350 NM. For the time spent flying stacks, the Pearson Chi-Square test also indicated no significant result ($\chi^2(141) = 114.0, p = 0.41$). Only a small reduction is seen from AMAN to XMAN250. Thereafter, the time spent in stacks remained constant.

Looking at Figures 5.2b, 5.2d, 5.2f and 5.2h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is AMAN. So for IAF ARTIP, the total delay reduces when extending the horizon by approximately 15% compared to the baseline condition.

IAF RIVER

The second IAF to look at is RIVER. Figure 5.3 graphically depicts the low-level delay absorption strategies for IAF RIVER, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson's Chi-Square test is used to test significance on categorical variables, where results are considered significant for $p \leq 0.05$.

Using the Pearson Chi-Square test, the number of aircraft that do not have to absorb any delays does not change significantly when extending the horizon ($\chi^2(66) = 78.53, p = 0.14$). However, when looking at Figures 5.3a, 5.3c, 5.3e and 5.3g, there seems to be more aircraft that do not have to absorb any delays when extending the horizon. This number of aircraft almost doubles when moving from AMAN to XMAN250, but thereafter seems to stagnate.

As explained in Section 4.4.3, only two delay absorption strategies are used for IAF RIVER: (extended) dogleg and stack. First looking at the number of doglegs, the Pearson

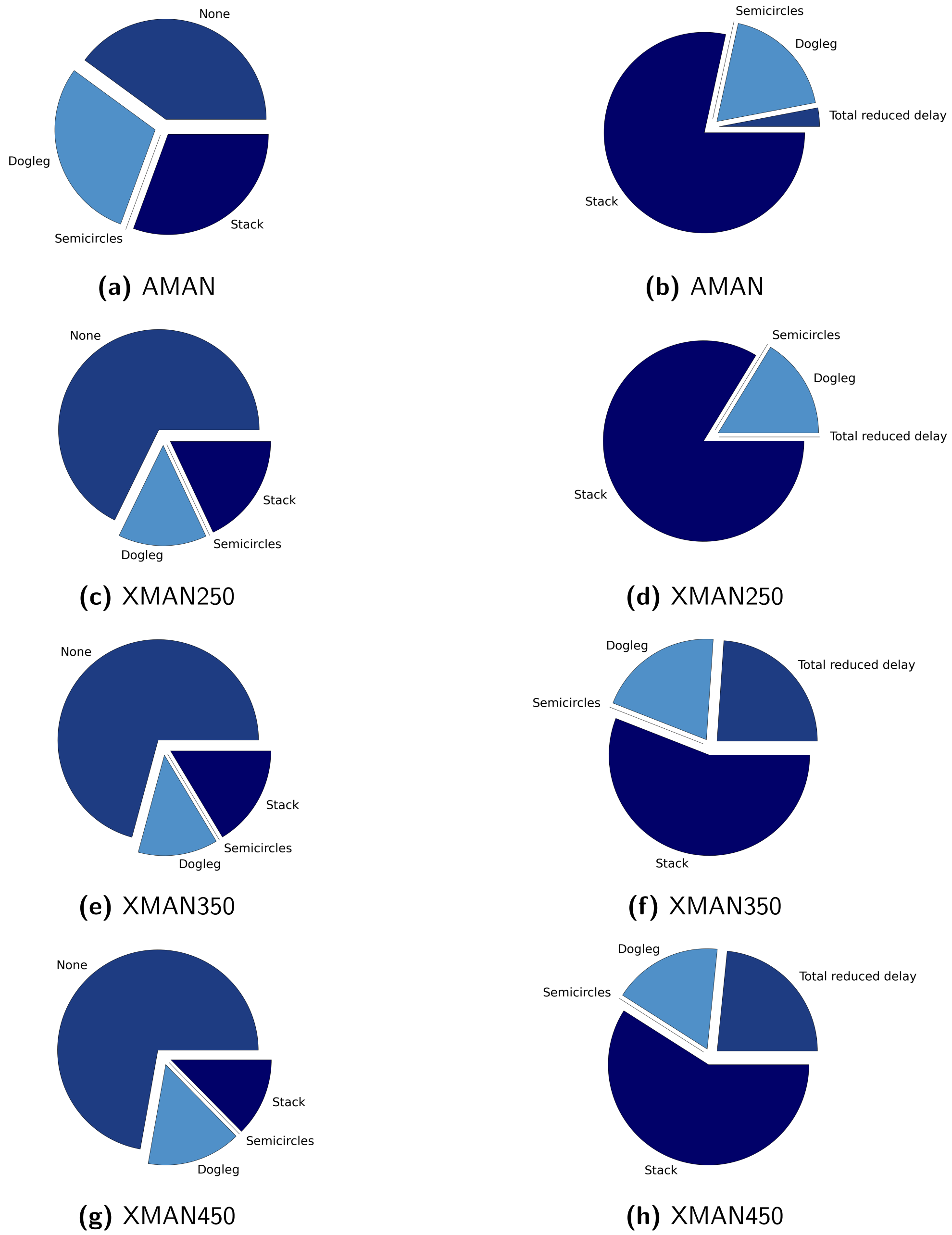


Figure 5.3: Scenario I: Low-level delay absorption strategy for Initial Approach Fix RIVER. Left: number of aircraft; right: amount of delay

Chi-Square test revealed no significant result ($\chi^2(36) = 49.91, p = 0.06$). Moving from AMAN to XMAN250, the number of doglegs seems to decrease. Beyond 250 NM, the number of doglegs seems to stay constant. The time spent flying doglegs could not be considered significant according to the Pearson Chi-Square test ($\chi^2(138) = 140.0, p = 0.44$). The amount of delay appears to stay constant throughout the extension of the horizon.

When looking at the number of aircraft subject to flying a minimum of one stack, the

Pearson Chi-Square test indicated no significant result ($\chi^2(45) = 50.67, p = 0.26$). Fewer aircraft are subject to flying a minimum of one stack when the horizon is extended to 250 NM, but thereafter the number of aircraft appears to stagnate. The Pearson Chi-Square test for time spent flying a minimum of one stack revealed no significant effect when extending the horizon ($\chi^2(138) = 140.0, p = 0.44$). For AMAN, over 75% of the total delay is absorbed in the stacks. There is a slight increase when moving to a 250 NM horizon, while extending the horizon to 350 NM reduces the stack delay to about 55% of the total delay. When moving to 450 NM, the stack delay slightly increased again.

Looking at Figures 5.3b, 5.3d, 5.3f and 5.3h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is XMAN250. For AMAN, there is a slight reduction of total delay. For XMAN350 and XMAN450, the total delay has decreased by almost 25%.

IAF SUGOL

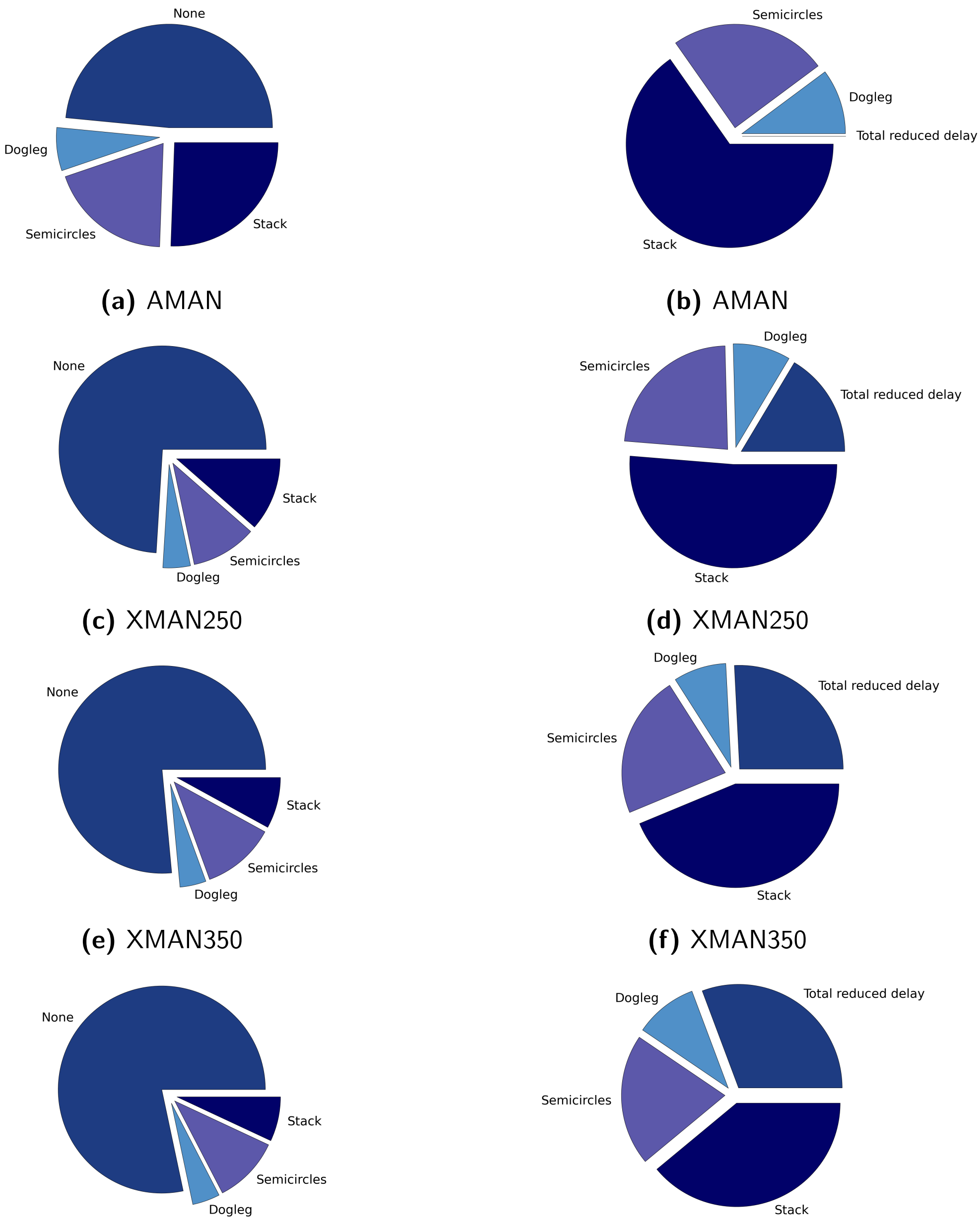
The last and third IAF to look at is SUGOL. Figure 5.4 shows the low-level delay absorption strategies for IAF SUGOL, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson's Chi-Square test is used to test significance on categorical variables, where results are considered significant for $p \leq 0.05$.

Using the Pearson Chi-Square test, an extension of the horizon did not imply significant results for aircraft that did not have to absorb any low-level delay ($\chi^2(57) = 56.73, p = 0.46$). Looking at Figures 5.4a, 5.4c, 5.4e and 5.4g, the number of aircraft that can continue directly into the TMA is about 50%. Extending the horizon caused an increase in number of aircraft without low-level delay to approximately 75%.

The number of aircraft subject to a dogleg did not significantly change when extending the horizon ($\chi^2(15) = 22.23, p = 0.10$). In fact, there appears to be a slight decrease in aircraft subject to doglegs when extending the horizon to 250 NM, but thereafter the number of aircraft stays constant. Looking at the time spent flying a dogleg, no significant result could be found ($\chi^2(135) = 138.67, p = 0.40$). The amount of delay for doglegs appears to stay constant.

For aircraft subject to semicircles, no significant result was seen by the Pearson Chi-Square test ($\chi^2(33) = 37.73, p = 0.26$). When extending the horizon to 250 NM, a decrease in aircraft subject to semicircles is seen. Beyond 250 NM, the number of aircraft subject to semicircles seems to slightly increase again. The time spent flying semicircles did not cause a significant effect according to the Pearson Chi-Square test ($\chi^2(141) = 114.0, p = 0.41$). The amount of delay for semicircles appears to stay constant.

Lastly, the number of aircraft subject to a minimum of one stack did not significantly change using the Pearson Chi-Square test ($\chi^2(48) = 55.27, p = 0.22$), even though a reduction is seen from 25% for AMAN to approximately 8% for XMAN450. It appears that the number of aircraft flying stacks reduces, while the number of aircraft flying semicircles increases. Apparently, the delay is shifted from stack to semicircles. The effect on time spent flying a minimum of one stack was also not significant according to



(a) AMAN **(b)** AMAN

(c) XMAN250 **(d)** XMAN250

(e) XMAN350 **(f)** XMAN350

(g) XMAN450 **(h)** XMAN450

Figure 5.4: Scenario I: Low-level delay absorption strategy for Initial Approach Fix SUGOL. Left: number of aircraft; right: amount of delay

the Pearson Chi-Square test ($\chi^2(117) = 120.89, p = 0.38$). However, the amount of delay for stacks does seem to decrease.

Looking at Figures 5.4b, 5.4d, 5.4f and 5.4h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is AMAN. So for IAF SUGOL, the total delay reduces when extending the horizon by over 25% compared to the baseline condition.

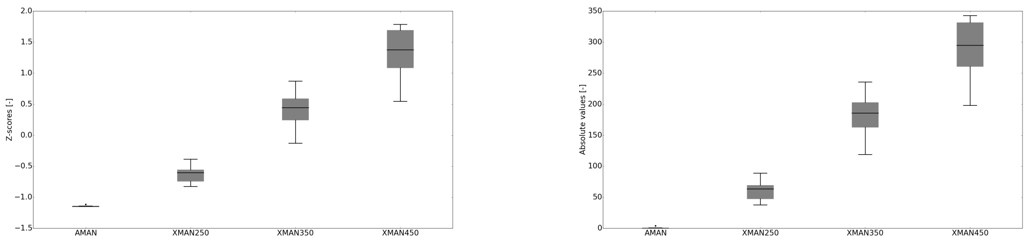
5.1.2 Arrival sequence stability

Knowing the amount of low-level delay that was absorbed prior to flying over the IAF, the arrival sequence stability can be assessed. The arrival sequence stability, as shown in Table 5.2, looks at the total number of STA revisions, the runway inter-arrival time, the number of sequence changes and IAF accuracy.

Table 5.2: Scenario I: Arrival sequence stability

Parameter	AMAN	XMAN250	XMAN350	XMAN450
# of STA revisions [-]	0.58	61.5	182.8	291.6
Inter-arrival time [s]	121.1	121.8	122.4	123.0
# of sequence changes [-]	4.3	54.8	103.7	119.2
IAF accuracy [s]	52.9	49.4	55.7	53.6

The number of STA revisions seems to greatly increase with an extension of the horizon, and so does the number of sequence changes. Both the inter-arrival time and the IAF accuracy seem to relatively stay constant. A more extensive analysis on each dependent variable is given below.

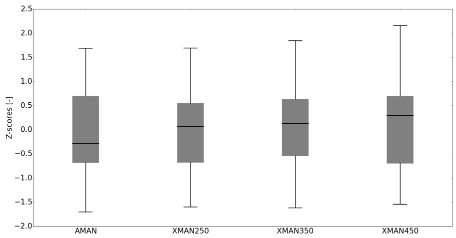


(a) Z-score

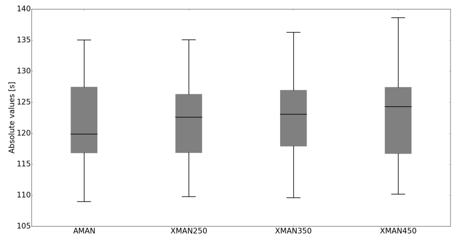
(b) Absolute value

Figure 5.5: Boxplots Scenario I: Arrival sequence stability – scheduled time of arrival revisions

Figure 5.5 shows the boxplots for STA revisions. The number of STA revisions is assessed to identify how often a landing slot is altered. A significant increase in STA revisions was seen using the main effects test ($\chi^2(3) = 36.0, p \leq 0.05$). Post-hoc tests revealed STA revisions increase significantly compared to the AMAN case with increasing horizon ($p \leq 0.0125$). A significant increase was also seen between XMAN250 and XMAN350 ($p \leq 0.0125$). The difference between AMAN and XMAN250 is already a multiplication factor of more than 100, and this factor only increases for extending horizon to over a factor of 500 between AMAN and XMAN450. It must be noted that the number of STA revisions for XMAN is too high to be anywhere near realistic. This will be further elaborated on in Chapter 6.



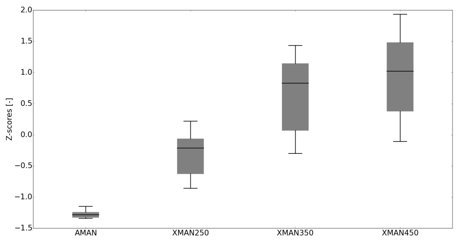
(a) Z-score



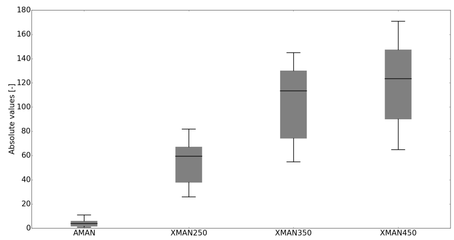
(b) Absolute value

Figure 5.6: Boxplots Scenario I: Arrival sequence stability – inter-arrival time

The inter-arrival time indicates the average time between two aircraft at the runway. Looking at inter-arrival time as shown in Figure 5.6, the main effects test showed no significance ($\chi^2(3) = 5.90, p = 0.12$). Looking at the average values, there seems to be a slight increase with extending horizon. However, this increase cannot be deemed significant.



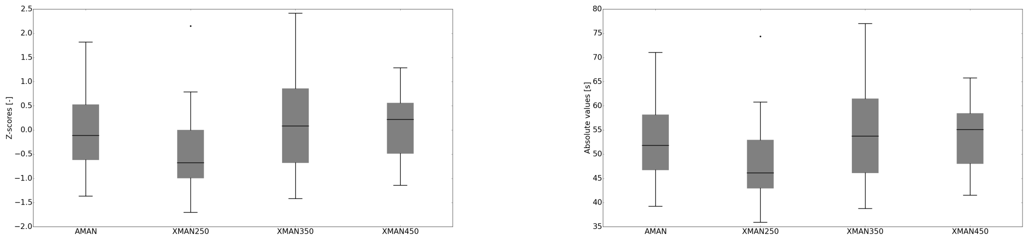
(a) Z-score



(b) Absolute value

Figure 5.7: Boxplots Scenario I: Arrival sequence stability – sequence changes

The number of sequence changes indicates the average number of landing slots revisions that have changed the approach sequence. Figure 5.7 indicates a significant effect between the results ($\chi^2(3) = 33.3, p \leq 0.05$). Post-hoc tests showed a significant difference with increasing horizon for all XMAN conditions compared to the AMAN condition ($p \leq 0.0125$). Furthermore, the result between XMAN250 and XMAN350 is also significant ($p \leq 0.0125$). The difference between AMAN and XMAN250 is more than a multiplication factor of 10, and this factor only increases for extending horizon up to a factor of 27 between AMAN and XMAN450. It must be noted that the number of sequence changes for XMAN is too high to be anywhere near realistic. This will be further elaborated on in Chapter 6.



(a) Z-score **(b)** Absolute value

Figure 5.8: Boxplots Scenario I: Arrival sequence stability – Initial Approach Fix accuracy

The IAF accuracy shows the accuracy with which aircraft pass the IAF compared to their EAT. The boxplots for IAF accuracy are graphically depicted in Figure 5.8. The main effects test does not show a significant effect for IAF accuracy ($\chi^2(3) = 4.50, p = 0.21$). It must be noted the IAF accuracy is not within the approach margin. The reason is that aircraft arriving late can only be accelerated up to the nominal speed. If, due to a miscalculation, the aircraft arrives later than its EAT and is already flying at its nominal speed, there is no other possibility of absorbing the negative delays.

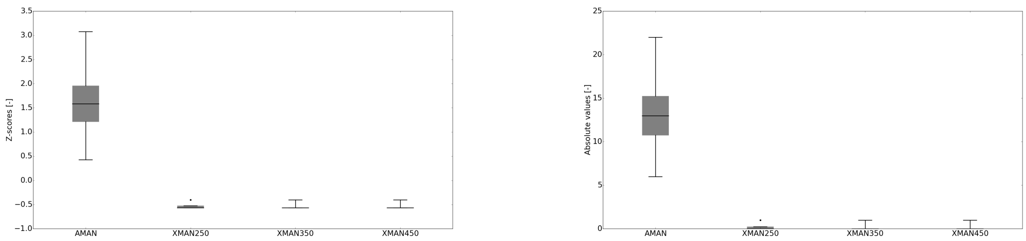
5.1.3 Flight plan changes

Flight plan changes is comprised of disturbed descents and speed changes, and tabulated in Table 5.3. Flight plan changes affect both pilots and controllers. Disturbed descents indicate whether the STAs and corresponding approach sequence was altered after TOD. Speed changes are divided in before and after TOD. It is assumed the speed changes before TOD are given by neighbouring centres, while speed changes after TOD are given by Amsterdam ACC.

Table 5.3: Scenario I: Flight plan changes

Parameter	AMAN	XMAN250	XMAN350	XMAN450
# of disturbed descents	13.1	0.25	0.17	0.17
# of speed changes (≥ 1 kts) before TOD	1.6	11.8	48.8	238.3
# of speed changes (≥ 1 kts) after TOD	7.5	5.0	7.5	50.9
# of speed changes (≥ 5 kts) before TOD	0.46	3.2	9.9	133.4
# of speed changes (≥ 5 kts) after TOD	1.7	2.1	2.5	17.6

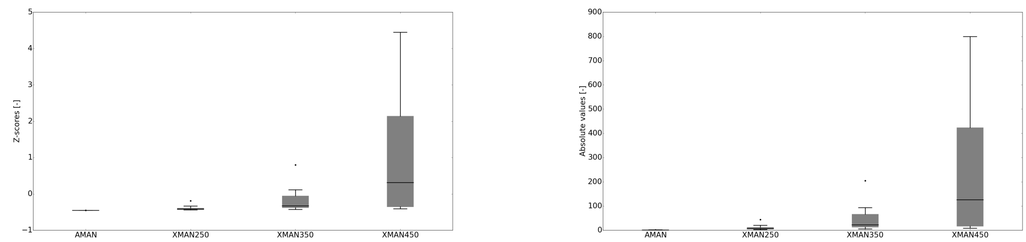
The number of disturbed descents greatly reduces when extending the horizon. The number of speed changes per aircraft is measured when the speed deviates by more than 1 kts and when the speed deviates by more than 5 kts. Before TOD, the number of speed changes increases. After TOD, in general the number of speed changes also increases. A more detailed analysis on each dependent variable is done below.



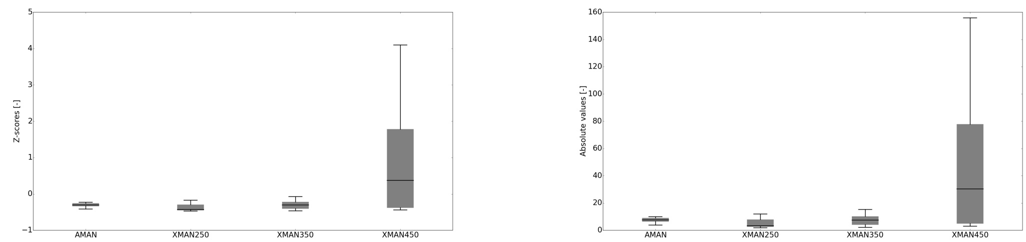
(a) Z-score **(b)** Absolute value

Figure 5.9: Boxplots Scenario I: Flight plan changes – Disturbed Descents

Figure 5.9 shows the boxplots for disturbed descents. A main effects test showed a significant effect on disturbed descents ($\chi^2(3) = 32.1, p \leq 0.05$). Compared to the AMAN condition, an increase in horizon significantly decreased the number of disturbed descents ($p \leq 0.0125$). Comparing XMAN250 and XMAN350, no significant effect was seen ($Z = -0.58, p = 0.56$). Extending the horizon will cause a significant reduction in disturbed descents.



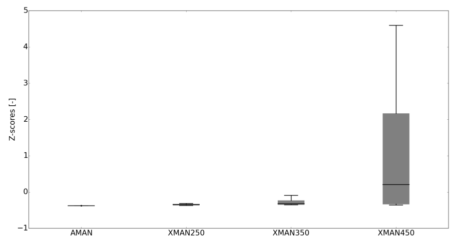
(a) Z-score – before TOD **(b)** Absolute value – before TOD



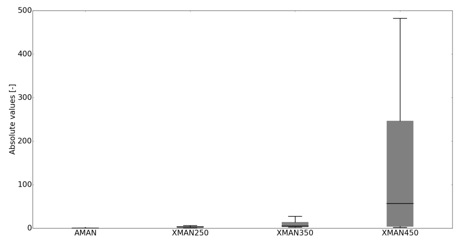
(c) Z-score – after TOD **(d)** Absolute value – after TOD

Figure 5.10: Boxplots Scenario I: Flight plan changes – speed changes ≥ 1 kts

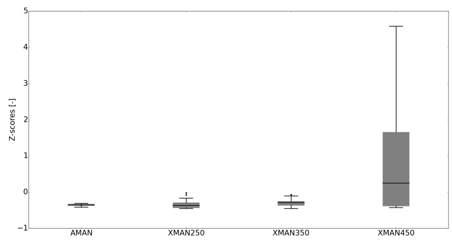
Speed changes ≥ 1 kts are graphically depicted in Figure 5.10. Speed changes before TOD are considered significant according to the main effects test ($\chi^2(3) = 32.7, p \leq 0.05$). Post-hoc tests revealed a significant effect for all XMAN conditions compared to the AMAN case ($p < 0.0125$), and also revealed a significant effect between XMAN250 and XMAN350 ($p \leq 0.0125$). This means the number of speed changes significantly increases with an extension of the horizon, i.e. the number of speed changes instructed by a neighbouring centre will increase. The main effects test for speed changes after TOD could also be identified as significant ($\chi^2(3) = 10.3, p \leq 0.05$). Post-hoc tests indicated a significant effect between AMAN and XMAN250 ($p \leq 0.0125$), however no significant effect was identified between AMAN and XMAN350 ($Z = -0.08, p = 0.94$) or AMAN and XMAN450 ($Z = -1.41, p = 0.16$). The results between XMAN250 and XMAN350 could neither be identified as significant ($Z = -2.28, p = 0.023$). However, there seems to be a tendency of increasing number of speed changes after 350 NM.



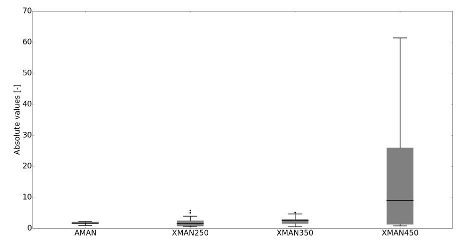
(a) Z-score – before TOD



(b) Absolute value – before TOD



(c) Z-score – after TOD



(d) Absolute value – after TOD

Figure 5.11: Boxplots Scenario I: Flight plan changes – speed changes $\geq$ 5 kts

Speed changes $\geq$ 5 kts are graphically depicted in Figure 5.11. The main effects test for speed changes before TOD was considered significant ($\chi^2(3) = 28.9, p \leq 0.05$). Post-hoc tests revealed all XMAN conditions compared to the AMAN condition could be considered significant ($p \leq 0.0125$), and a significant effect was also seen between XMAN250 and XMAN350 ($p \leq 0.0125$). In all cases, the number of speed changes significantly increased with extending horizon. Lastly, the main effects test for speed changes after TOD could not be considered significant ($\chi^2(3) = 4.3, p = 0.23$). However, there seems to be a tendency of an increase in speed changes with an extension of the horizon, although not significant.

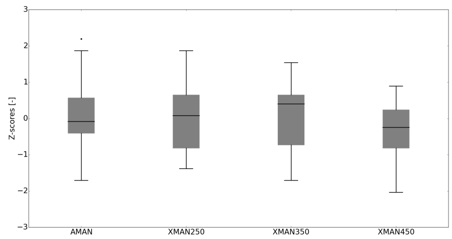
5.1.4 Traffic bunching

Table 5.4 gives the number of traffic bunches per IAF. Using the new traffic bunch definition in Section 2.4.2, the margin at EHAA CBAS equals the approach margin, i.e. 30 seconds.

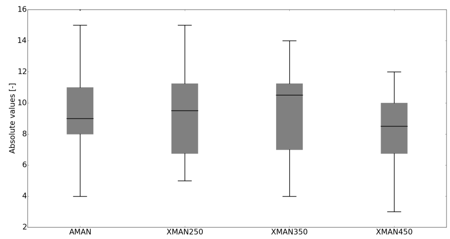
Table 5.4: Scenario I: Average number of traffic bunches per Initial Approach Fix

Parameter	AMAN	XMAN250	XMAN350	XMAN450
ARTIP	9.75	9.50	9.58	8.17
RIVER	3.42	2.92	2.92	3.33
SUGOL	6.08	5.25	4.08	4.58

For IAF ARTIP, the number of traffic bunches fluctuates between 8 and 10. The number of bunches for RIVER fluctuates around 3, and lastly, the number of traffic bunches for SUGOL fluctuates between 4 and 6. More information on the traffic bunches per IAF is given below.



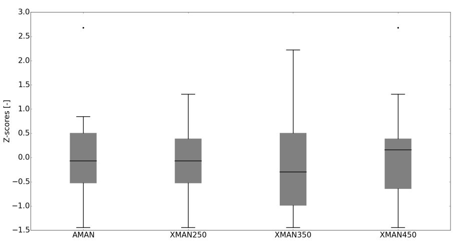
(a) Z-score



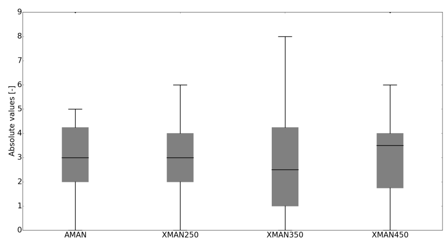
(b) Absolute value

Figure 5.12: Boxplots Scenario I: Traffic bunches for Initial Approach Fix ARTIP

Figure 5.12 shows the boxplots of traffic bunches for IAF ARTIP. A main effects test showed the results could not be considered significant ($\chi^2(3) = 4.46, p = 0.22$). The boxplot for each horizon almost fully overlaps with the other boxplots, so indeed no difference in number of traffic bunches can be seen.



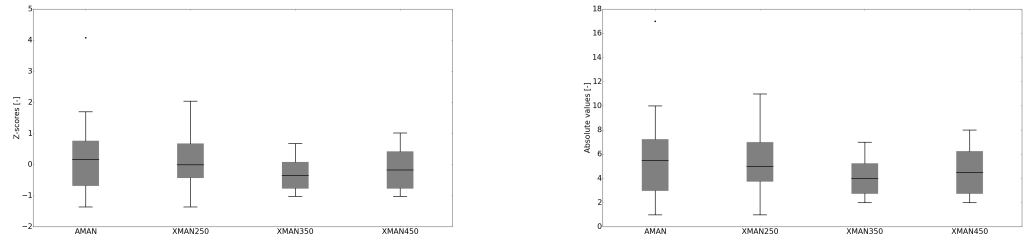
(a) Z-score



(b) Absolute value

Figure 5.13: Boxplots Scenario I: Traffic bunches for Initial Approach Fix RIVER

Figure 5.13 graphically depicts the boxplots of the number of traffic bunches for IAF RIVER. The main effects test revealed no significant effect for an extension of the horizon ($\chi^2(3) = 0.682, p = 0.88$). Looking at the average values, no clear effect can be seen when extending the horizon. Next to that, all boxplots seem to overlap, meaning the number of traffic bunches does not change.



(a) Z-score **(b)** Absolute value

Figure 5.14: Boxplots Scenario I: Traffic bunches for Initial Approach Fix SUGOL

Lastly, Figure 5.14 shows the boxplots of the number of traffic bunches for IAF SUGOL. No significant effect was found using the main effects test ($\chi^2(3) = 1.78, p = 0.62$). The boxplot for each horizon overlaps with the other boxplots indicating that no effect is seen on the number of traffic bunches when extending the horizon.

5.2 Scenario II: Tighter Approach Margin

The second scenario looked at the tighter approach margin and the performance on the arrival manager. In this section, the following terminology will be used as defined in Section 4.2:

- A-M120: AMAN with approach margin of 120 seconds (Scenario II-i).
- A-M30: AMAN with approach margin of 30 seconds (Scenario II-ii).
- X-M120: XMAN with approach margin of 120 seconds (Scenario II-iii).
- X-M30: XMAN with approach margin of 30 seconds (Scenario II-iv).

Two pairs were investigated in the post-hoc test: A-M30 – A-M120 and X-M30 – X-M120. With these two pairs, a Bonferroni correction of two is used to reduce the Type I error. A Type I error is the error of observing a statistical difference, while in fact there is no difference. Post-hoc tests were considered significant when $p \leq 0.025$.

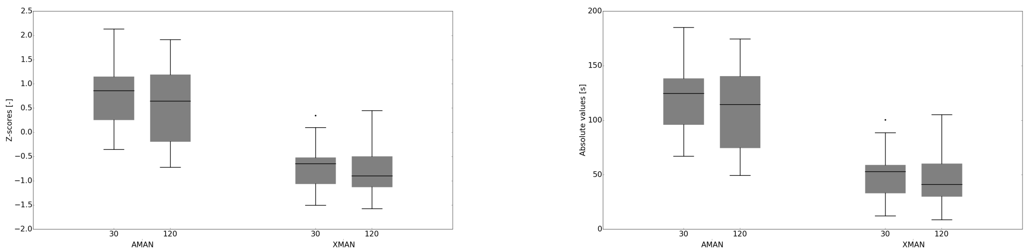
5.2.1 Low-level delay absorption

Low-level delay indicates the amount of delay that should still be absorbed prior to entering the TMA at the EAT within the approach margin. Delay absorption using only speed-control was possible until waypoint almost-IAF (last waypoint 15 NM before the IAF), after which a low-level delay absorption strategy was chosen dependent on the amount of delay required to be absorbed prior to entering the TMA. To shortly summarise what has been presented in Section 4.4.3, doglegs and semicircles were flown for relatively small delays (up to 150 seconds), while holdings (also called stacks) were flown for delays greater than 150 seconds. Table 5.5 indicates, on average, how much delay was absorbed at a low-level, how many aircraft were subject to a certain strategy and the amount of delay absorbed per strategy.

Table 5.5: Scenario II: Low-level delay absorption

Parameter	AMAN		XMAN	
Approach Margin [s]	**30**	**120**	**30**	**120**
Low-level delay [s]	124.3	112.0	51.7	47.0
# of doglegs [-]	17	2	7	2
Time in doglegs [s]	64.3	66.1	67.9	120.9
# of semicircles [-]	19	5	9	3
Time in semicircles [s]	95.5	132.0	91.4	123.7
# of stacks [-]	40	40	19	19
Time in stacks [s]	339.0	347.1	285.0	282.4

The results in Table 5.5 show the average low-level delay slightly increases for a tighter approach margin. The number of doglegs, semicircles and stacks indicates the average number of aircraft subject to each strategy. The number of doglegs and number of semicircles seems to increase, while the number of stacks seems to stay constant. The time spent in doglegs, semicircles or stacks indicates the average time an aircraft spent flying a certain strategy. For all cases with the exception of time spent in stacks for XMAN, the time spent flying a certain strategy decreased. The time spent in stacks for XMAN actually slightly increased. More information on the low-level delay is given below.



(a) Z-score **(b)** Absolute value

Figure 5.15: Boxplots Scenario II: Low-level delay absorption – low-level delay

Looking at low-level delay as seen in Figure 5.15, a main effects test for AMAN showed a significant effect using a tighter approach margin ($\chi^2(1) = 8.33, p \leq 0.05$), while the main effects test for XMAN showed no significant effect ($\chi^2(1) = 1.33, p = 0.25$). Post-hoc tests did not confirm a significant effect between A-M30 and A-M120 ($Z = -2.12, p = 0.034$). Looking at the boxplots, there indeed appears to be no difference in results between the two approach margins.

IAF ARTIP

In order to look at the type of low-level delay, the data was split up for each IAF. Figure 5.16 shows the low-level delay absorption strategy for IAF ARTIP, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson Chi-Square test is used to test significance on categorical variables, where results are considered significant for $p \leq 0.05$.

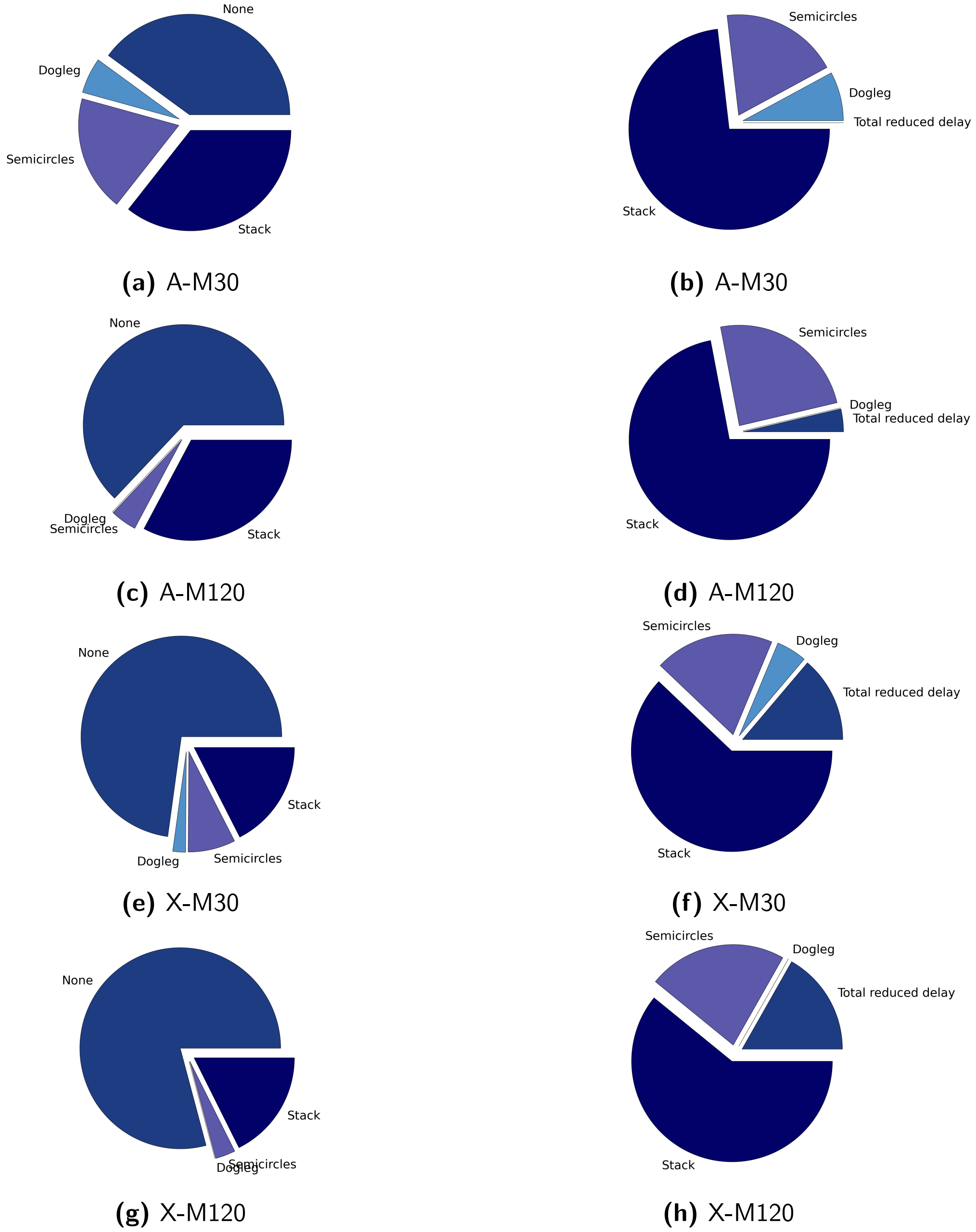


Figure 5.16: Scenario II: Low-level delay absorption strategy for Initial Approach Fix ARTIP. Left: number of aircraft; right: amount of delay

Using the Pearson Chi-Square test, the number of aircraft that do not have to absorb any delays does not change significantly for a tighter approach margin for AMAN ($\chi^2(13) = 20.0, p = 0.10$) and neither for XMAN ($\chi^2(14) = 16.3, p = 0.29$). Looking at Figures 5.16a, 5.16c, 5.16e and 5.16g, it seems, however, that the number of aircraft, for both AMAN and XMAN, reduces. For A-M120, about 65% of all aircraft do not have to absorb any delays, while for A-M30 the number drops below 50%. The difference between X-M120 and X-M30 is less, in the order of 5%.

Looking at the number of aircraft subject to a dogleg, the Pearson Chi-Square test showed a significant result within AMAN ($\chi^2(6) = 24.0, p \leq 0.05$) and within XMAN ($\chi^2(3) = 12.0, p \leq 0.05$). For an approach margin of 120 seconds, there are no aircraft subject to doglegs. For a tighter margin, the number of aircraft increases. When looking at the time spent flying a dogleg, the Pearson Chi-Square test revealed a significant result by comparing A-M120 with A-M30 ($\chi^2(12) = 24.0, p \leq 0.05$), but no significant result by comparing X-M120 and X-M30 ($\chi^2(8) = 12.0, p = 0.15$). However, again in both cases, there is no delay absorbed in doglegs for an approach margin of 120 seconds, while there is delay absorbed for an approach margin of 30 seconds.

The Pearson Chi-Square test revealed a significant effect within AMAN when looking at the number of aircraft flying semicircles ($\chi^2(12) = 21.0, p \leq 0.05$), while no such effect was revealed for XMAN ($\chi^2(8) = 9.33, p = 0.32$). In both cases, there seems to be a tendency of an increase in aircraft subject to semicircles. The time spent flying semicircles was not found to be significant for AMAN ($\chi^2(23) = 24.0, p = 0.40$) and nor for XMAN ($\chi^2(2) = 24.0, p = 0.35$). There seems to be a slight decrease in semicircles delay.

According to the Pearson Chi-Square test, the number of aircraft subject to a stack could not be found significant for AMAN ($\chi^2(14) = 9.33, p = 0.81$), and nor for XMAN ($\chi^2(13) = 9.33, p = 0.75$). The number of aircraft seems to stay constant when applying a tighter approach margin. For the time spent flying stacks, the Pearson Chi-Square test also indicated no significant result for AMAN ($\chi^2(22) = 22.0, p = 0.46$), and nor for XMAN ($\chi^2(22) = 22.0, p = 0.46$). The time spent flying stacks also seems to stay constant.

Looking at Figures 5.16b, 5.16d, 5.16f and 5.16h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is A-M30. For both AMAN and XMAN, there seems to be a reduction in total reduced delay when applying a tighter approach margin.

IAF RIVER

The second IAF to look at is RIVER. Figure 5.17 graphically depicts the low-level delay absorption strategies for IAF RIVER, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson Chi-Square test is used on categorical variables, where results are considered significant for $p \leq 0.05$.

Using the Pearson Chi-Square test, the number of aircraft that do not have to absorb any delays does not change significantly for a tighter approach margin for AMAN ($\chi^2(16) = 17.3, p = 0.36$) and neither for XMAN ($\chi^2(13) = 16.0, p = 0.25$). Looking at Figures 5.17a, 5.17c, 5.17e and 5.17g, there seems to be a reduction in number of aircraft that can continue without a low-level delay absorption strategy into the TMA. The reduction is less for XMAN compared to AMAN.

As explained in Section 4.4.3, only two delay absorption strategies are used for IAF RIVER: (extended) dogleg and stack. First looking at the number of doglegs, the Pearson Chi-Square test revealed a significant effect for both AMAN ($\chi^2(10) = 22.0, p \leq 0.05$) and

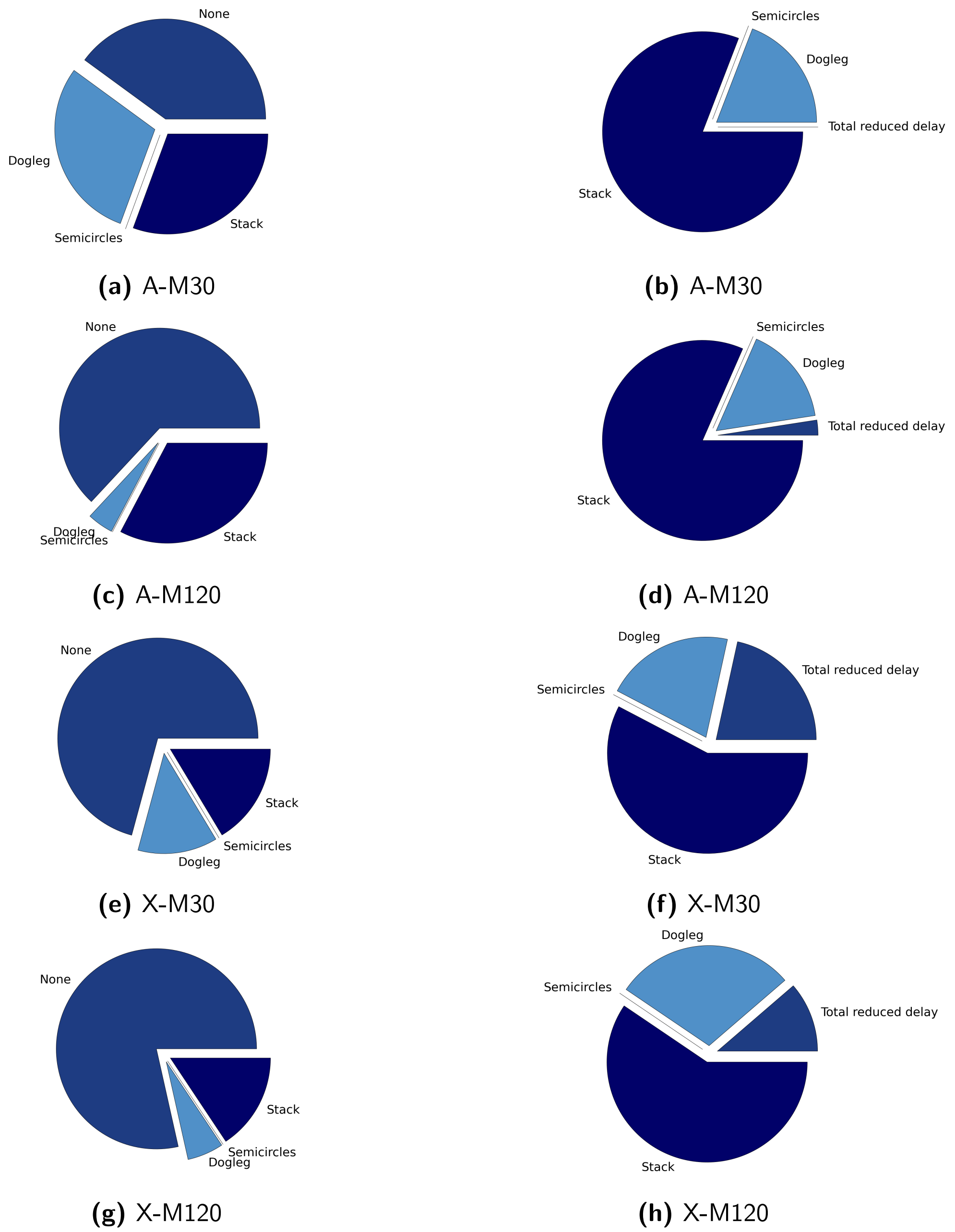


Figure 5.17: Scenario II: Low-level delay absorption strategy for Initial Approach Fix RIVER. Left: number of aircraft; right: amount of delay

XMAN ($\chi^2(7) = 17.2, p \leq 0.05$). There is a significant increase in number of doglegs when applying a tighter approach margin. Looking at the time spent flying doglegs, the Pearson Chi-Square test did not reveal a significant effect for AMAN ($\chi^2(18) = 24.0, p = 0.16$), and neither for XMAN ($\chi^2(23) = 24.0, p = 0.40$). For AMAN, there appears to be a small increase in dogleg delay, while for XMAN the dogleg delay seems to reduce. This result should be further investigated to identify why the difference between AMAN and XMAN is caused.

Last but not least, the number of stacks is not significant according to the Pearson Chi-Square test for AMAN ($\chi^2(9) = 5.87, p = 0.75$), and neither for XMAN ($\chi^2(9) = 9.53, p = 0.39$). In both cases, the number of stacks seems to stay constant. The stack delay could also not be identified as significant. The Pearson Chi-Square test for AMAN identified no significance ($\chi^2(22) = 22.0, p = 0.46$), and also the results for XMAN could not be deemed significant ($\chi^2(22) = 22.0, p = 0.46$). The stack delay also seems to stay constant.

Looking at Figures 5.17b, 5.17d, 5.17f and 5.17h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is A-M30. Between A-M120 and A-M30, a small reduction in total reduced delay is seen when applying a tighter approach margin. Between X-M120 and X-M30, the total reduced delay actually increases. This result should also be further investigated to identify why the difference between AMAN and XMAN is caused.

IAF SUGOL

The last and third IAF to look at is SUGOL. Figure 5.18 shows the low-level delay absorption strategies for IAF SUGOL, where the left pie graphs indicate the number of aircraft subject to a low-level delay absorption strategy and the right pie graphs indicate the total amount of delay per absorption strategy. To apply a statistical analysis to these results, the Pearson Chi-Square test is used on categorical variables, where results are considered significant for $p \leq 0.05$.

Using the Pearson Chi-Square test, the number of aircraft that do not have to absorb any delays does not change significantly for a tighter approach margin for AMAN ($\chi^2(16) = 15.3, p = 0.50$) and neither for XMAN ($\chi^2(12) = 19.0, p = 0.09$). Looking at Figures 5.18a, 5.18c, 5.18e and 5.18g, there appears to be a decrease in number of aircraft that do not have to absorb any low-level delay. For A-M120, about 70% of all aircraft do not have to absorb any delays. Tightening the approach margin causes a reduction to less than 50%, although this reduction cannot be identified as significant. For XMAN, the reduction is less severe.

The number of doglegs, based on the Pearson Chi-Square test, changes significantly when applying a tighter approach margin for both AMAN ($\chi^2(4) = 24.0, p \leq 0.05$) and XMAN ($\chi^2(4) = 17.1, p \leq 0.05$). In both cases, there is an increase in number of doglegs. The time spent flying a dogleg causes a significant effect for AMAN according to the Pearson Chi-Square test ($\chi^2(12) = 24.0, p \leq 0.05$), while for XMAN no significant effect was seen ($\chi^2(10) = 17.1, p = 0.71$). When applying a tighter margin, the dogleg delay seems to increase.

The Pearson Chi-Square test indicates that the increase in number of semicircles is significant for AMAN ($\chi^2(11) = 21,3, p \leq 0.05$), but the slight increase cannot be deemed significant for XMAN ($\chi^2(7) = 13.5, p = 0.06$). The delay associated to flying semicircles could not be deemed significant for AMAN ($\chi^2(23) = 24.0, p = 0.40$) and neither for XMAN ($\chi^2(20) = 24.0, p = 0.24$). The portion of semicircles delay seems to stay constant.

Lastly, the number of aircraft subject to flying a stack does not change significantly according to the Pearson Chi-Square test for AMAN ($\chi^2(12) = 7.33, p = 0.84$) and

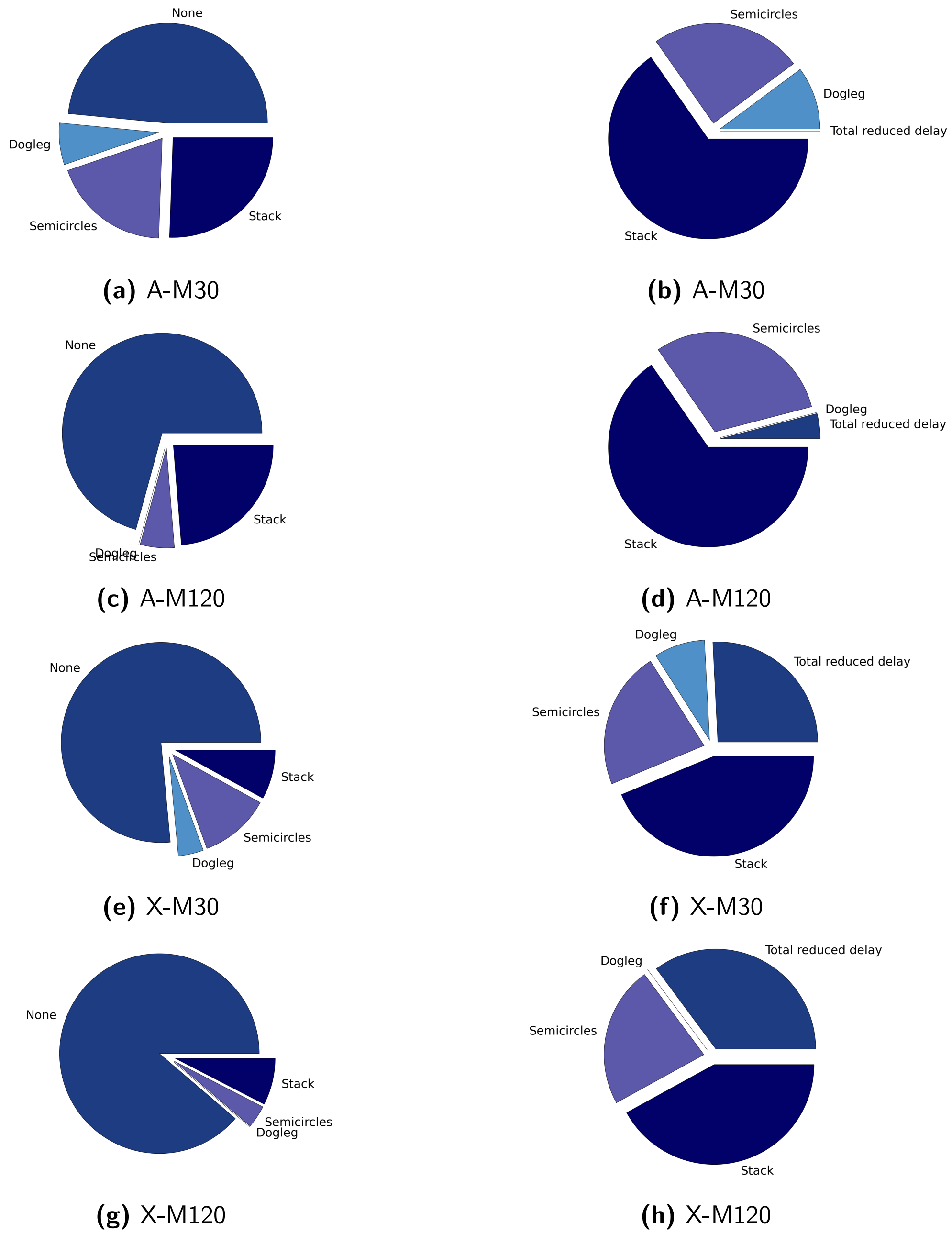


Figure 5.18: Scenario II: Low-level delay absorption strategy for Initial Approach Fix SUGOL. Left: number of aircraft; right: amount of delay

neither for XMAN ($\chi^2(9) = 9.20, p = 0.42$). For AMAN, the percentage of number of aircraft lies around 25%. For XMAN, the percentage of number of aircraft lies around 10%. The delay associated to stacks does not seem to change. For AMAN, the Pearson Chi-Square test indicated no significant effect ($\chi^2(20) = 18.0, p = 0.59$). For XMAN, the results also indicated no significant effect ($\chi^2(16) = 16.0, p = 0.45$). For both cases, the percentage of stack delays remains constant.

Looking at Figures 5.18b, 5.18d, 5.18f and 5.18h, the so-called 'total reduced delay' can be seen. The total reduced delay is the reduction in delay compared to the baseline. The baseline, in this case, is A-M30. When applying a tighter approach margin to AMAN and XMAN, the total reduced delay decreases.

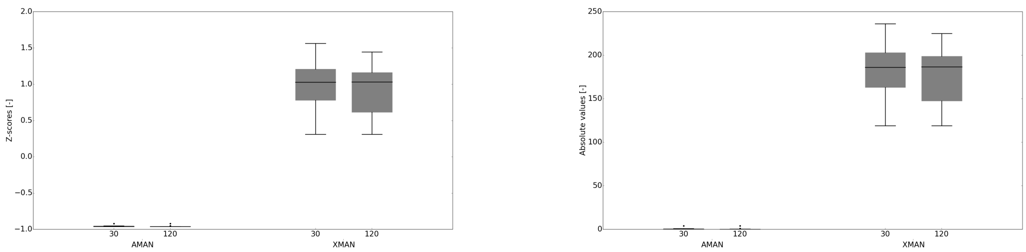
5.2.2 Arrival sequence stability

Knowing the amount of low-level delay that was absorbed prior to flying over the IAF, the arrival sequence stability can be assessed. The arrival sequence stability, as shown in Table 5.6, looks at the total number of STA revisions, the runway inter-arrival time, the number of sequence changes and IAF accuracy.

Table 5.6: Scenario II: Arrival sequence stability

Parameter	AMAN		XMAN	
Approach Margin [s]	**30**	**120**	**30**	**120**
# of STA revisions [-]	0.58	0.50	182.8	176.3
Inter-arrival time [s]	121.1	120.8	122.4	122.4
# of sequence changes [-]	4.3	4.2	103.7	92.3
IAF accuracy [s]	52.9	77.4	55.7	71.8

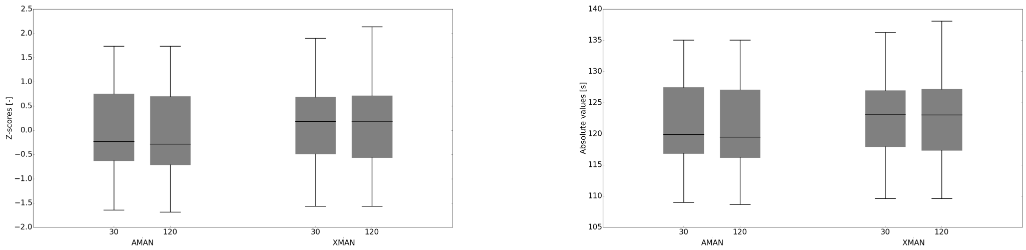
For AMAN, the number of STA revisions and number of sequence changes seems to stay constant, and so does the inter-arrival time. The IAF accuracy actually reduces. Looking at XMAN, there is a slight increase in number of STA revisions and number of sequence changes. The inter-arrival time seems to stay constant, and a slight decrease is seen in IAF accuracy. A more extensive analysis on each dependent variable is given below.



(a) Z-score **(b)** Absolute value

Figure 5.19: Boxplots Scenario II: Arrival sequence stability – scheduled time of arrival revisions

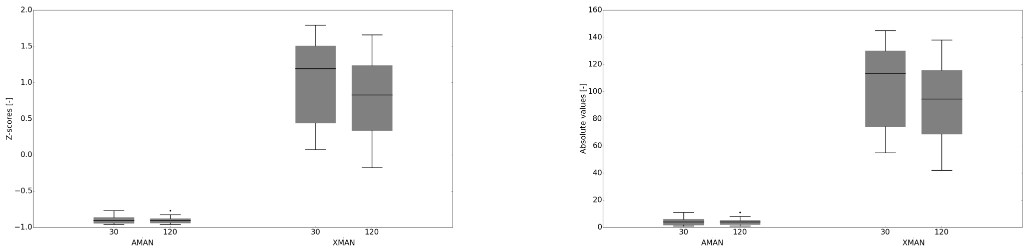
Figure 5.19 shows the boxplots of the STA revisions for AMAN and XMAN. The number of STA revisions is assessed to identify how often a landing slot is altered. The main effects test for AMAN indicated no significant result ($\chi^2(1) = 1.00, p = 0.32$), indicating no influence of the approach margin on the number of STA revisions. For XMAN, the main effects test also indicated no significant result ($\chi^2(1) = 1.60, p = 0.21$). The influence of the approach margin on the number of STA revisions is therefore minimal.



(a) Z-score **(b)** Absolute value

Figure 5.20: Boxplots Scenario II: Arrival sequence stability – inter-arrival time

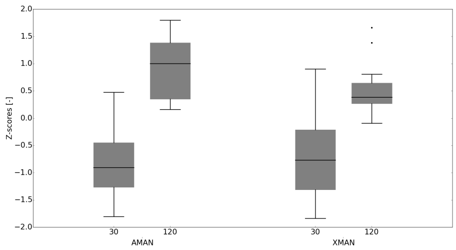
The inter-arrival time indicates the average time between two aircraft at the runway. Looking at inter-arrival time in Figure 5.20, the main effects test for AMAN indicated no significant effect ($\chi^2(1) = 0.82, p = 0.37$), and neither did the test for XMAN ($\chi^2(1) = 1.33, p = 0.25$). The average values seem to stay constant at approximately 120 seconds, which indicates there is no influence of a tighter approach margin on the inter-arrival time at the runway.



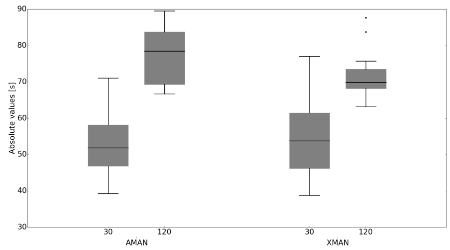
(a) Z-score **(b)** Absolute value

Figure 5.21: Boxplots Scenario II: Arrival sequence stability – sequence changes

The number of sequence changes indicates the average number of landing slots revisions that have changed the approach sequence. The boxplots on sequence changes are given in Figure 5.21. Using a main effects test, the result was found not to be significant for AMAN ($\chi^2(1) = 0.33, p = 0.56$) and neither for XMAN ($\chi^2(1) = 2.27, p = 0.13$). Using a tighter approach margin tends to increase the number of sequence changes, however this effect cannot be considered significant.



(a) Z-score



(b) Absolute value

Figure 5.22: Boxplots Scenario II: Arrival sequence stability – Initial Approach Fix accuracy

The IAF accuracy shows the accuracy with which aircraft pass the IAF compared to their EAT. The boxplots for IAF accuracy are graphically depicted in Figure 5.22. A main effects test revealed a significant effect for AMAN ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test between A-M30 and A-M120 also indicated a significant effect ($p \leq 0.025$). A main effects test for XMAN also revealed a significant effect ($\chi^2(1) = 8.33, p \leq 0.05$), where the post-hoc test between X-M30 and X-M120 also indicated a significant effect ($p \leq 0.025$). The effect is expected as using an approach margin of 120 seconds allows controllers to let aircraft pass the IAF with a higher delay (up to 120 seconds) compared to an approach margin of 30 seconds where a maximum of 30 seconds of delay is allowed. It must be noted the IAF accuracy with an approach margin of 30 seconds is outside the bounds. The reason for this difference is the fact that aircraft that arrive late compared to the EAT can only increase their speed up to the nominal conditions. If the nominal speed is reached, but the delay remains negative, no corrective actions are taken to reduce the negative delays. As a result, aircraft will pass the IAF outside the approach margin and the IAF accuracy will decrease.

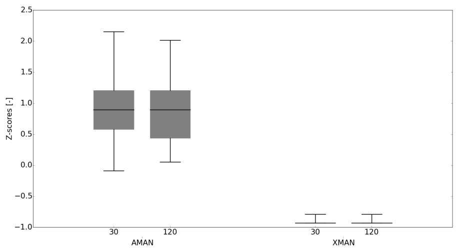
5.2.3 Flight plan changes

The flight plan changes are given in Table 5.7, and affect both pilots and controllers. Disturbed descents indicate whether the STAs and corresponding approach sequence was altered after TOD. Speed changes are divided in before and after TOD. It is assumed the speed changes before TOD are given by neighbouring centres, while speed changes after TOD are given by Amsterdam ACC.

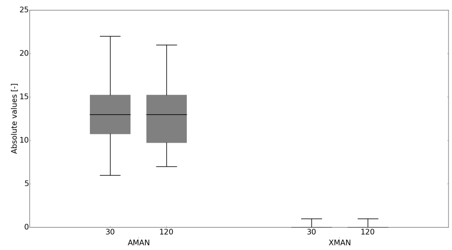
Table 5.7: Scenario II: Flight plan changes

Parameter	**AMAN**		**XMAN**	
Approach Margin [s]	**30**	**120**	**30**	**120**
# of disturbed descents	13.1	13.1	0.17	0.17
# of speed changes ($\geq$ 1 kts) before TOD	1.6	1.1	48.8	3.6
# of speed changes ($\geq$ 1 kts) after TOD	7.5	4.1	7.5	1.3
# of speed changes ($\geq$ 5 kts) before TOD	0.46	0.32	9.9	1.2
# of speed changes ($\geq$ 5 kts) after TOD	1.7	0.95	2.5	0.71

The number of disturbed descents does not change when a tighter approach margin is used. The number of speed changes per aircraft is measured when the speed deviates by more than 1 kts and when the speed deviates by more than 5 kts. For AMAN, the number of speed changes before TOD seems to stay constant, while the number of speed changes after TOD increases. For XMAN, the number of speed changes before and after TOD increases. A more detailed analysis on each dependent variable is done below.



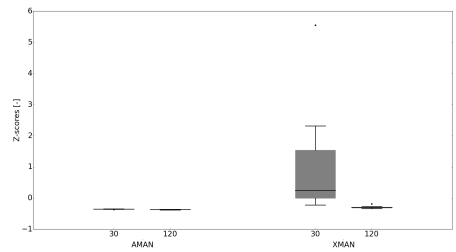
(a) Z-score



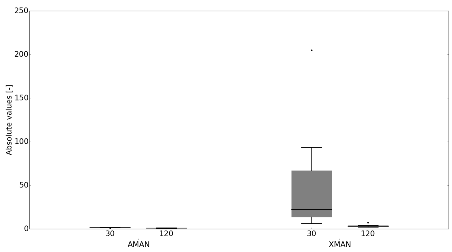
(b) Absolute value

Figure 5.23: Boxplots Scenario II: Flight plan changes – Disturbed Descents

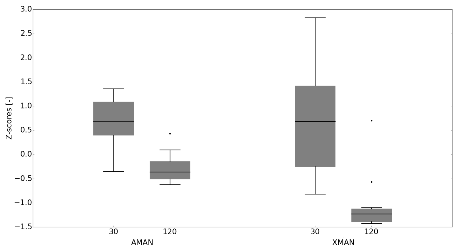
Figure 5.23 shows the boxplots of disturbed descents using different approach margins. The main effects test for AMAN showed no significance ($\chi^2(1) = 0.11, p = 0.74$). The main effects test for XMAN was inconclusive, as the results were equal. The number of disturbed descents does not seem to change when applying a tighter approach margin.



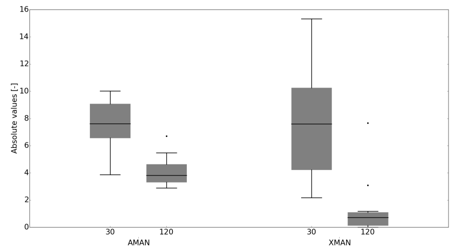
(a) Z-score – before TOD



(b) Absolute value – before TOD



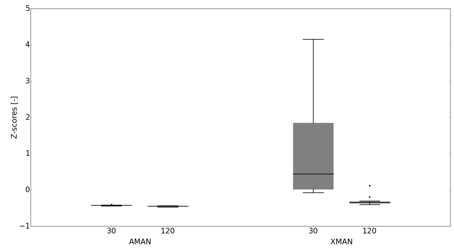
(c) Z-score – after TOD



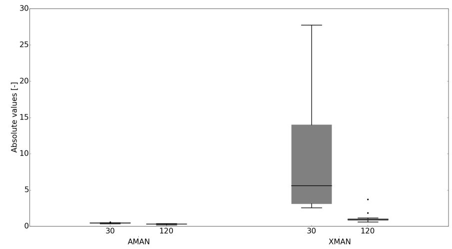
(d) Absolute value – after TOD

Figure 5.24: Boxplots Scenario II: Flight plan changes – speed changes ≥ 1 kts

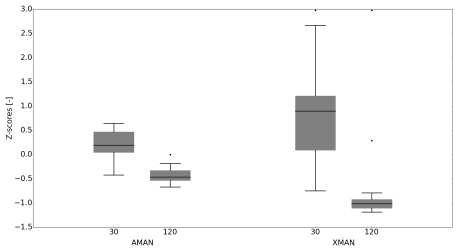
Figure 5.24 shows the boxplots for the speed changes ≥ 1 kts done by aircraft during cruise and descent. The main effects test for AMAN for speed changes before TOD showed a significant effect ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test also revealed a significant effect between A-M30 and A-M120 ($p \leq 0.025$). The main effects test for speed changes after TOD also showed a significant effect ($\chi^2(1) = 5.33, p \leq 0.05$), where the post-hoc test concluded a significant effect between A-M30 and A-M120 ($p \leq 0.025$). For XMAN, the main effects test for speed changes before TOD showed a significant effect ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test also revealed a significant effect between X-M30 and X-M120 ($p \leq 0.025$). The main effects test for speed changes after TOD also showed a significant effect ($\chi^2(1) = 5.33, p \leq 0.05$), where the post-hoc test concluded a significant effect between X-M30 and X-M120 ($p \leq 0.025$). Concluding, there is a significant increase in number of speed changes for both AMAN and XMAN, and both before and after TOD.



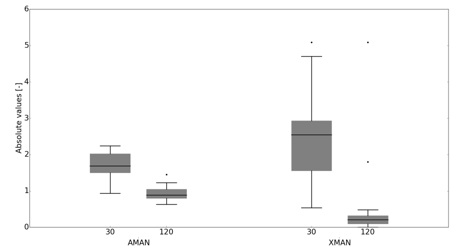
(a) Z-score – before TOD



(b) Absolute value – before TOD



(c) Z-score – after TOD



(d) Absolute value – after TOD

Figure 5.25: Boxplots Scenario II: Flight plan changes – speed changes ≥ 5 kts

Figure 5.25 shows the boxplots for the speed changes ≥ 5 kts done by aircraft during cruise and descent. The main effects test for AMAN for speed changes ≥ 5 kts before TOD showed a significant effect ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test also revealed a significant effect between A-M30 and A-M120 ($p \leq 0.025$). The main effects test for speed changes ≥ 5 kts after TOD also showed a significant effect ($\chi^2(1) = 8.33, p \leq 0.05$), where the post-hoc test concluded a significant effect between A-M30 and A-M120 ($p \leq 0.025$). For XMAN, the main effects test for speed changes ≥ 5 kts before TOD showed a significant effect ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test also revealed a significant effect between X-M30 and X-M120 ($p \leq 0.025$). The main effects test for speed changes ≥ 5 kts after TOD also showed a significant effect ($\chi^2(1) = 8.33, p \leq 0.05$), where the post-hoc test concluded a significant effect between X-M30 and X-M120 ($p \leq 0.025$). Concluding, there is a significant increase in number of speed changes ≥ 5 kts for both AMAN and XMAN, and both before and after TOD.

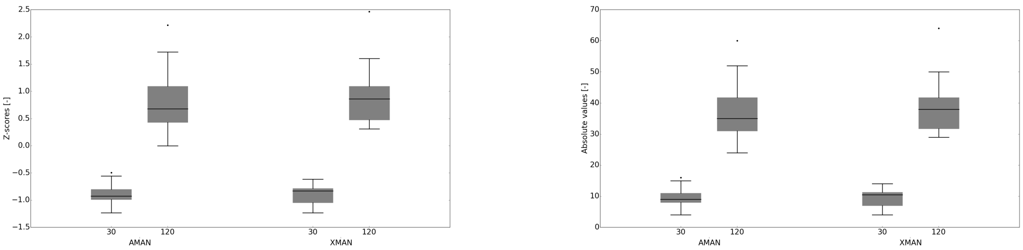
5.2.4 Traffic bunching

Lastly, the number of traffic bunches per IAF is tabulated in Table 5.8. Using the new traffic bunch definition in Section 2.4.2, the margin at EHAA CBAS equals the approach margin. The number of traffic bunches is incomparable for different approach margins, since the margins at EHAA CBAS differ. As a result, it is only possible to compare the traffic bunches with the same approach margin.

Table 5.8: Scenario II: Average number of traffic bunches per Initial Approach Fix

Parameter	**AMAN**		**XMAN**	
Approach Margin [s]	**30**	**120**	**30**	**120**
ARTIP	9.75	37.58	9.58	39.17
RIVER	3.42	13.33	2.92	15.08
SUGOL	6.08	21.08	4.08	19.58

The number of traffic bunches for ARTIP, RIVER and SUGOL appears to decrease with a tighter approach margin. More information on the traffic bunches per IAF is given below.

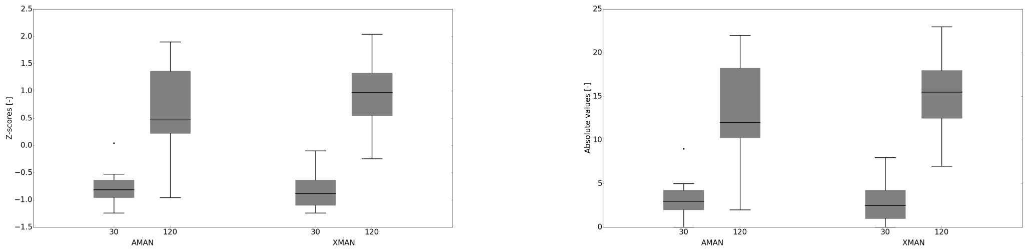


(a) Z-score

(b) Absolute value

Figure 5.26: Boxplots Scenario II: Traffic bunches for Initial Approach Fix ARTIP

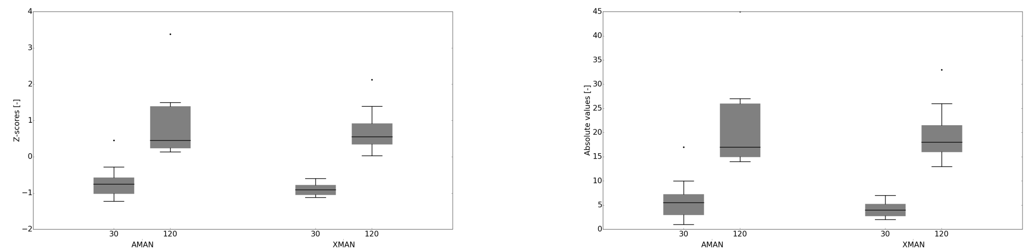
For IAF ARTIP, see Figure 5.26, a main effects test for AMAN showed a significant effect of traffic bunches ($\chi^2(1) = 12.0, p \leq 0.05$), where the difference between A-M30 and A-M120 was deemed significant according to the post-hoc test ($p \leq 0.025$). The main effects test for XMAN also indicated a significant effect of traffic bunches ($\chi^2(1) = 12.0, p \leq 0.05$), and post-hoc tests confirmed the significance between X-M30 and X-M120 ($p \leq 0.025$). This effect can be expected as two different margins are used to calculate the traffic bunches. A more detailed analysis on the number of traffic bunches for IAF ARTIP is done in Section 6.2.



(a) Z-score **(b)** Absolute value

Figure 5.27: Boxplots Scenario II: Traffic bunches for Initial Approach Fix RIVER

The boxplots for IAF RIVER are depicted in Figure 5.27. A main effects test showed a significant result for AMAN ($\chi^2(1) = 11.0, p \leq 0.05$). Post-hoc tests concluded the result was significant between A-M30 and A-M120 ($p \leq 0.025$). The main effects test for XMAN also indicated a significant result ($\chi^2(1) = 12.0, p \leq 0.05$), where the post-hoc test also concluded significance between X-M30 and X-M120 ($p \leq 0.025$). This effect can be expected as two different margins are used to calculate the traffic bunches. A more detailed analysis on the number of traffic bunches for IAF RIVER is done in Section 6.2.



(a) Z-score **(b)** Absolute value

Figure 5.28: Boxplots Scenario II: Traffic bunches for Initial Approach Fix SUGOL

The boxplots for the third IAF, SUGOL, are presented in Figure 5.28. According to the main effects test for AMAN, the results found were significant ($\chi^2(1) = 12.0, p \leq 0.05$). The main effects test for XMAN also showed a significant effect ($\chi^2(1) = 12.0, p \leq 0.05$). The same results were found compared to the other two IAFs: the results were significant between A-M30 and A-M120 ($p \leq 0.025$) and between X-M30 and X-M120 ($p \leq 0.025$). This effect can be expected as two different margins are used to calculate the traffic bunches. A more detailed analysis on the number of traffic bunches for IAF SUGOL is done in Section 6.2.

Chapter 6

Discussion

In the current chapter, a discussion is held based on the outcome of the simulations. The two sub-research questions are discussed using the hypothesis in Section 3.4 and the results in Chapter 5. At the end, the research question as described in Section 3.2 is answered.

6.1 Scenario I: Extension of Horizon

The first research sub-question to be answered is:

I. What is the effect of the extension of the horizon on the arrival manager performance?

Based on the results as shown in Table 6.1, there is definitely an effect of the extension of the horizon on the arrival manager performance. This section discusses these results for each hypothesis for the first scenario.

Table 6.1: Scenario I: Experiment Statistical Results

	Main Test	Post-hoc Tests			
		AMAN-XMAN250	AMAN-XMAN350	AMAN-XMAN350	XMAN250-XMAN350
Disturbed descents	x	x	x	x	o
IAF accuracy	o				
Inter-arrival time	o				
Low-level delay absorption	x	x	x	x	x
Sequence changes	x	x	x	x	x
Speed changes before TOD $\geq$ 1 kts	x	x	x	x	x
Speed changes after TOD $\geq$ 1 kts	x	x	o	o	o
Speed changes before TOD $\geq$ 5 kts	x	x	x	x	x
Speed changes after TOD $\geq$ 5 kts	o				
STA revisions	x	x	x	x	x
Traffic bunch ARTIP	o				
Traffic bunch RIVER	o				
Traffic bunch SUGOL	o				

x significant o not significant

6.1.1 Low-level delay absorption

The first hypothesis (H1-1) stated the amount of low-level delay would decrease. Looking at low-level delay absorption shows extending the horizon will cause an increase in aircraft that can enter the TMA without delay absorption. Furthermore, the amount of low-level delay indeed significantly decreased, thereby confirming the hypothesis. For the three IAFs, it seems a minimum amount of low-level delay absorption is reached for 350 NM. Extending the horizon further causes only a slight decrease in the amount of delay that is absorbed. An explanation can be found in the runway capacity and pop-up flights. The flights inbound to Schiphol Airport need to land at two runways. Since flights are not pre-planned, the approach sequence can only be made once the aircraft is airborne. Since the runway is assigned to each aircraft before the start of the simulation, there is no possibility of an approach sequence optimisation. Extending the horizon will cause peaks up to 100% of pop-up flights scheduled to land, see Figure 6.1. With an average pop-up ratio of about 50%, there is simply no more capacity to handle all the flights without having delays. Even a speed reduction would not suffice to absorb the necessary delay, and as such low-level delay is required. Sequence optimisation could further reduce the low-level delay.

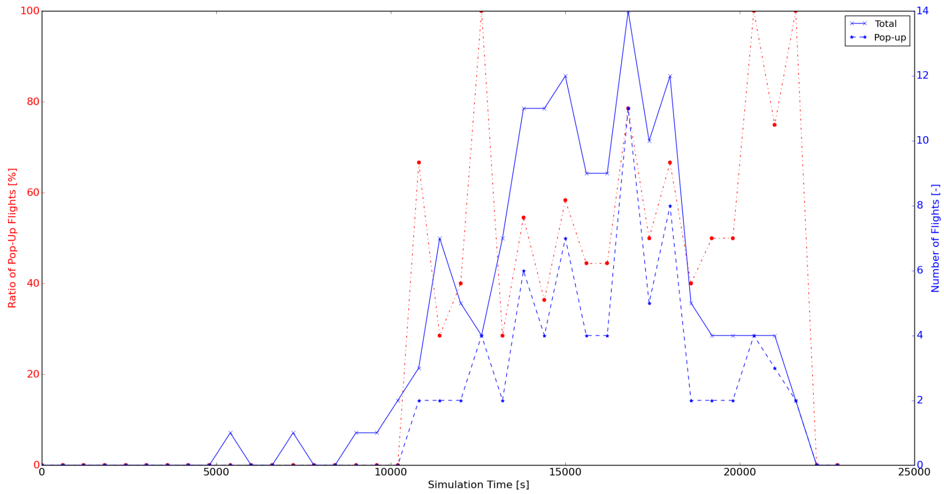


Figure 6.1: Pop-up ratio (red), number of pop-up flights (blue dashed) and number of total flights (blue continuous)

During the simulations, conflict detection and resolution was not used. The sequencer module only allows for conflict-free landings. As a consequence, the flown trajectories cannot be assumed conflict-free. Furthermore, the impact on other traffic (non-Schiphol or departing Schiphol traffic) is unknown. Part of this unknown impact is accounted for using a speed offset and speed offset deviation, as aircraft arrive later than initially estimated. The flown trajectories within Dutch airspace could not be assumed conflict-free. Since low-level delay absorption is taking place in the last 15 NM before the IAF, it is possible the lateral separation between two aircraft is less than 5 NM. However, in reality aircraft will be instructed to absorb the low-level delay at a greater distance from the IAF. Absorbing the delays earlier in time should result in conflict-free trajectories, while the total low-level delay would remain the same.

6.1.2 Arrival sequence stability

The number of STA revisions was hypothesised to decrease (H1-3), as well as the number of sequence changes (H1-2). With an extension of the horizon, the number of STA revisions and sequence changes actually increase significantly, thereby not supporting the hypothesis. As the horizon is extended, a sequence is made earlier in time. Since an inaccuracy is added to the flying time, extending the horizon will cause the sequence to change more often as the TP is not fed with accurate predictions. These inaccurate predictions will cause revised STAs and more sequence changes. Furthermore, if an aircraft enters the planning horizon at, e.g., 450 NM, there is an increased chance of a pop-up flight that is still to depart. Once the pop-up flight has departed, its ETA is calculated and the approach sequence is updated to include the new pop-up flight. An extension of the horizon will thereby cause multiple recalculations and sequence changes. The impact on the controller and the pilot, based on these revisions and changes, should be further investigated. Next to that, the increase in sequence changes of more than a factor 10 when increasing the horizon to 250 NM cannot be deemed realistic. The approach sequence is optimised during the simulation, however the result is not realistic and suitable for real-life purposes. As the sequence keeps changing, the controller cannot give a proper speed instruction to absorb delays. For future research, the sequencer should be improved to generate less STA revisions and sequence changes, and thereby become more reliable.

6.1.3 TMA operations

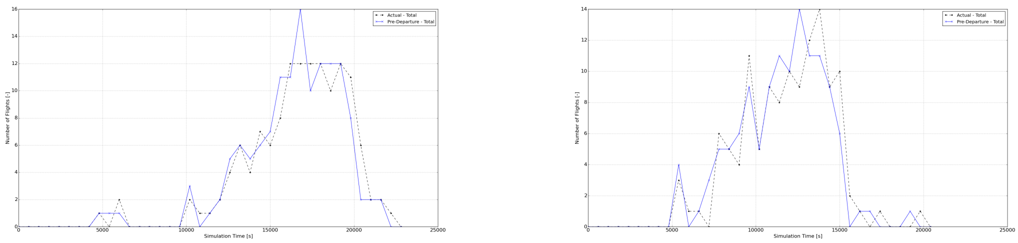
The TMA operations have been simplified by applying fixed arrival routes from the IAF towards the runway. Looking at the inter-arrival time, there seems to be no significant increase or decrease when extending the horizon. This supports the hypothesis (H1-5). Furthermore, no significant change was identified when looking at IAF accuracy, which is also in line with the hypothesis (H1-4). As stated in Chapter 5, it must be noted the IAF accuracy is not within the approach margin. The reason is that aircraft arriving late can only be accelerated up to the nominal speed. If, due to a miscalculation, the aircraft arrives later than its EAT and is already flying at its nominal speed, there is no other possibility of absorbing the negative delays. The effect seems negligible as controllers, in reality, will have multiple solutions for absorbing negative delays. An example is to give a direct route and thereby shortening the flying time. For further research, the possibility of applying front-loading in ARSIM should be investigated, as well as solutions to absorb negative delay. The TMA operation is therefore not likely to be affected by an extension of the horizon.

6.1.4 Flight plan changes

An improvement that is caused by making the sequence earlier in time is the number of disturbed descents. The number of STA revisions after TOD significantly reduced to fewer than one aircraft, which is in line with the hypothesis (H1-6). The sequence is therefore optimised during the descent phase of flight. Looking at the number of speed changes per aircraft, there is a significant increase when extending the horizon. This is in line with the hypothesis (H1-7). The number of speed changes $\geq$ 1 kts before TOD increases by a factor 6 for 250 NM up to almost a factor of 150 for 450 NM. The number of speed changes $\geq$ 1 kts after TOD slightly decreases for 250 NM, but thereafter increases again to over 50 speed changes for 450 NM. The number of speed changes $\geq$ 5 kts increases for an extension of the horizon. It must be noted that the number of speed changes necessary to absorb en-route delay do not represent the actual speed instructions an air traffic controller would give. The number of speed changes were calculated continuously, while air traffic controllers give discrete speed instructions. For 250 NM, on average three speed changes of 5 kts are needed before TOD. As three speed instructions per aircraft is an increase to the R/T used by the controller, the controller could also choose to give one instruction of 15 kts instead. The effect of discrete instructions should therefore be investigated. Furthermore, once the delay is above 30 seconds, continuous speed changes are made to reduce the delay below the approach margin. However, it might be possible that it is better to wait until the delay reached a certain value, a so-called delay threshold. The delay threshold does not have to be equal to the approach margin. The effect of using a delay threshold may also be researched, as Dutch controllers may use the remaining delay to optimise the sequence before aircraft pass the IAF.

6.1.5 Traffic bunches

Lastly, the number of traffic bunches remains constant with an extension of the planning horizon, which does not support the hypothesis (H1-8). Traffic bunches can never be fully diminished, unless the full 4D trajectory of each aircraft is known and can be adhered to. Furthermore, the inbound-outbound peak system at Schiphol Airport and the disturbance of airport and en-route operations on the traffic flow will always cause peaks in the actual traffic received. Dependent on the scenario, the estimated traffic peaks may be reduced by using an extended planning horizon (Figure 6.2a), or actually cause traffic peaks where no peaks were estimated (Figure 6.2b). However, in both cases, at the end of the simulation traffic inbound to Schiphol Airport is arriving later than initially planned. The inbound peak is thus extended in time and shifted backwards. This result was also found in the research study on the effect on en-route delay absorption on the runway throughput [W. Vermeersch, 2015]. Unfortunately, since an extension of the horizon does not guarantee a reduction of estimated traffic peaks, a reduction in the number of traffic bunches is not likely to be caused.



(a) Scenario A **(b)** Scenario B

Figure 6.2: Two scenarios indicating the pre-departure estimate (blue) and actual traffic received (black)

6.2 Scenario II: Tighter Approach Margin

The second research sub-question to be answered is:

II. What is the effect of the tighter approach margin on the arrival manager performance?

Based on the results as seen in Table 6.2, there seems to be an effect of the tighter approach margin on the arrival manager performance. This section discusses these results for each hypothesis for the second scenario.

Table 6.2: Scenario II: Experiment Statistical Results

	Main Test		Post-hoc Tests	
	AMAN	XMAN	AMAN 30-AMAN 120	XMAN 30-XMAN 120
Disturbed descents	o	†		†
IAF accuracy	x	x	x	x
Inter-arrival time	o	o		
Low-level delay absorption	x	o	o	
Sequence changes	o	o		
Speed changes before TOD $\geq$ 1 kts	x	x	x	x
Speed changes after TOD $\geq$ 1 kts	x	x	x	x
Speed changes before TOD $\geq$ 5 kts	x	x	x	x
Speed changes after TOD $\geq$ 5 kts	x	x	x	x
STA revisions	o	o		
Traffic bunch ARTIP	x	x	x	x
Traffic bunch RIVER	x	x	x	x
Traffic bunch SUGOL	x	x	x	x

† inconclusive x significant o not significant

6.2.1 Low-level delay absorption

Firstly, looking at low-level delay absorption shows no significant effect when applying a tighter approach margin. The hypothesis (H2-1) is therefore not supported. There is, however, a small tendency of more low-level delay. This extra delay can be attributed to the fact that there is a limit to en-route delay absorption, while aircraft are sequenced with a tighter margin. When aircraft cannot absorb any more delays en-route, the remaining delay should be absorbed at low-level. For all three IAFs, fewer aircraft enter the TMA without delay absorption when a tighter approach margin is used. The number of aircraft subject to a delay absorption strategy increases, while the total reduced delay decreases. The impact of a tighter approach margin on the low-level delay is less great for XMAN compared to AMAN. As aircraft are able to absorb delays en-route, the approach margin does not cause a significant increase in low-level delay. For AMAN, all delays are absorbed during the descent phase of flight meaning more delays need to be absorbed in a shorter time frame. As a result, the increase in low-level delay for AMAN is higher, although still not significant.

6.2.2 Arrival sequence stability

Arrival sequence stability will give information about the number of STA revisions and sequence changes. When applying a tighter approach margin, the number of STA revisions and sequence changes stay constant. This does not support the hypothesis for the number of sequence changes (H2-2), nor for the number of STA revisions (H2-3), which stated that the number of sequence changes and STA revisions would increase. However, there seems to be a small increase for XMAN. Even though this effect is not significant, the result is interesting as the number of STA revisions and sequence changes does not seem to be related to the approach margin. However, an explanation can be found for this phenomenon. The TP receives updates on the ETA of each aircraft, including aircraft with a given STA. Delays are calculated by subtracting the ETA from the STA. For any approach margin, the pilot will need to change the speed of the aircraft when the delay is greater than the approach margin. By changing the speed of the aircraft, the ETA will change again. When new aircraft arrive within the planning horizon, their ETA may be earlier than the new ETA of the other aircraft. As a result, an STA revision is done and the sequence may be updated. The process of changing the speed of the aircraft will take place earlier in time for aircraft subject to a tighter margin, meaning a higher variability in ETA and thus the number of STA revisions and sequence changes may increase.

6.2.3 Flight plan changes

Looking at the number of disturbed descents, there is no significant effect when applying a tighter approach margin. This is not in line with the hypothesis (H2-6). The tighter approach margin does have a significant effect on the number of speed changes per aircraft, which is in line with hypothesis (H2-7). There is a significant increase in number of speed changes $\geq$ 1 kts and $\geq$ 5 kts, both before and after TOD. The increase is caused by the fact that aircraft will be given speed advisories earlier in time when the delay is too high. Instead of waiting for a two minute delay, the aircraft will get advisories when the delay is more than 30 seconds. It must again be noted the number of speed changes do not correspond to the number of speed instructions given by a controller, as the speed instructions are discrete and the number of speed changes are calculated on a continuous level.

6.2.4 TMA operations

The TMA operations have been simplified by applying fixed arrival routes from the IAF towards the runway. Looking at the inter-arrival time, there seems to be no influence of the tighter approach margin, which supports hypothesis (H2-5). The inter-arrival time stays constant around 120 seconds. Applying a tighter approach margin should therefore not influence the TMA operations. The accuracy over the IAF actually increased, which is related to the approach margin, and confirms the hypothesis (H2-4). For an approach margin of 120 seconds, the aircraft will pass the IAF at EAT ± 120 seconds instead of EAT ± 30 seconds for a 30 seconds margin. As a consequence, the accuracy should increase. The IAF accuracy for an approach margin of 30 seconds is outside the 30 seconds region. The main reason is the fact that aircraft cannot accelerate beyond their nominal speeds and cannot fly directs if the delay is negative. In real life, aircraft with negative delays will fly at a higher altitude for a longer period of time or will receive a direct route. As the altitudes and routes are currently fixed in the simulation, the aircraft do not have any other means of absorbing negative delay. The effect seems negligible as controllers, in reality, will have multiple solutions for absorbing negative delays. These solutions should be researched and may be added to ARSIM to improve the simulation.

6.2.5 Traffic bunches

Lastly, a tighter approach margin has a significant effect on the number of traffic bunches, i.e. the number of traffic bunches reduces for a tighter approach margin. This is in line with hypothesis (H2-8). However, the reason for this significant effect is the use of two different CBAS margins. With the current definition on traffic bunching as explained in Section 2.4.2, the time between two aircraft at the EHAA CBAS horizon is used. This time, also called CBAS margin, corresponds to the approach margin. So for an approach margin of 30 seconds, two aircraft are in a traffic bunch if they both cross the EHAA CBAS horizon within 30 seconds. Looking at an approach margin of 120 seconds, two aircraft are in a traffic bunch if they both cross the EHAA CBAS horizon within 120 seconds. However, as two different approach margins are used, the EHAA CBAS margin also differs and thus a comparison in traffic bunches is not possible. In order to compare the traffic bunches, the CBAS margin needs to be the same. In other words, it is possible to compare the number of traffic bunches for an approach margin of 30 seconds and an approach margin of 120 seconds, as long as the CBAS margin is the same.

Table 6.3 shows the results of this analysis, where results were found significant for $p \leq 0.05$. For each approach margin, two CBAS margins are used to calculate the number of traffic bunches. Looking at a CBAS margin of 30 seconds for ARTIP, the result between the two approach margins is not significant ($\chi^2(1) = 0.09, p = 0.76$). Neither is the result for a CBAS margin of 120 seconds for ARTIP ($\chi^2(1) = 2.27, p = 0.13$). The results for RIVER indicate no significant effect for a 30 seconds margin ($\chi^2(1) = 0.50, p = 0.48$), and neither for a 120 seconds margin ($\chi^2(1) = 2.27, p = 0.13$). Lastly, the traffic bunches for SUGOL do not show a significant effect for a CBAS margin of 30 seconds ($\chi^2(1) = 2.27, p = 0.13$), but also no significant effect for a CBAS margin of 120 seconds ($\chi^2(1) = 1.60, p = 0.21$). It must therefore be concluded that the number of traffic bunches is not influenced by the approach margin, which is not in line with the hypothesis (H2-8).

Table 6.3: Scenario II: Number of traffic bunches per approach margin with different CBAS margins, per Initial Approach Fix

Approach Margin [s]	**30**		**120**	
CBAS margin [s]	**30**	**120**	**30**	**120**
ARTIP	9.58	37.33	9.58	39.17
RIVER	2.92	14.17	3.33	15.08
SUGOL	4.08	18.92	5.58	19.58

Finally, an answer to the following research question should be found:

To what extent is traffic bunching influenced by the use of cross-border arrival management at Schiphol Airport?

The results as presented and discussed per research sub-question show no significant effect on the number of traffic bunches when using an extended horizon or a tighter approach margin. Does that mean XMAN cannot contribute to a better arrival system? Well, with the introduction of XMAN, a drastic increase in the number of STA revisions and sequence changes is seen. The ACC controllers need to cope with these sequence changes, while performing their normal tasks. Without a stable sequence, XMAN will not be deemed reliable. However, during the simulations aircraft were constantly monitored and received speed advisories continuously when the delay was outside the approach margin. This situation could be improved if a certain delay threshold would be introduced before speed advisories would be given. As long as the delay threshold is not reached, a shift in sequence would not have consequences. The introduction of a delay threshold should be further investigated to introduce a more stable XMAN.

On a more positive note, the low-level delay is significantly reduced. Already a reduction of 50% is seen when the horizon is extended to 250 NM. This reduction and the significant decrease of disturbed descents shows XMAN does improve the arrival process within Dutch airspace. Almost no sequence changes occur after TOD and fewer aircraft are subject to less amount of low-level delay. The ACC controllers will therefore benefit from XMAN, as less aircraft are required to absorb delays and the sequence is stable for aircraft within the Dutch airspace.

Looking back at the research question and the results, there is apparently no influence of XMAN on the number of traffic bunches. The question therefore remains, what would influence the number of traffic bunches? To understand what would influence the number of bunches, the definition of traffic bunches should be revisited: *A traffic bunch is defined as a second aircraft crossing EHAA CBAS within a certain margin of the first aircraft.* According to the definition, traffic is bunched if, at least, two aircraft cross the EHAA CBAS horizon within a certain margin. So the chance of a traffic bunch is highest if many aircraft are inbound to Schiphol Airport. Looking at the distribution of arrivals and departures at Schiphol Airport throughout a day (Figure 6.3), significant arrival peaks can be seen. For example, between 06:40 and 07:00 UTC a total of 24 aircraft landed at Schiphol Airport, while in the next twenty minutes (07:00 - 07:20 UTC) only eight aircraft landed.

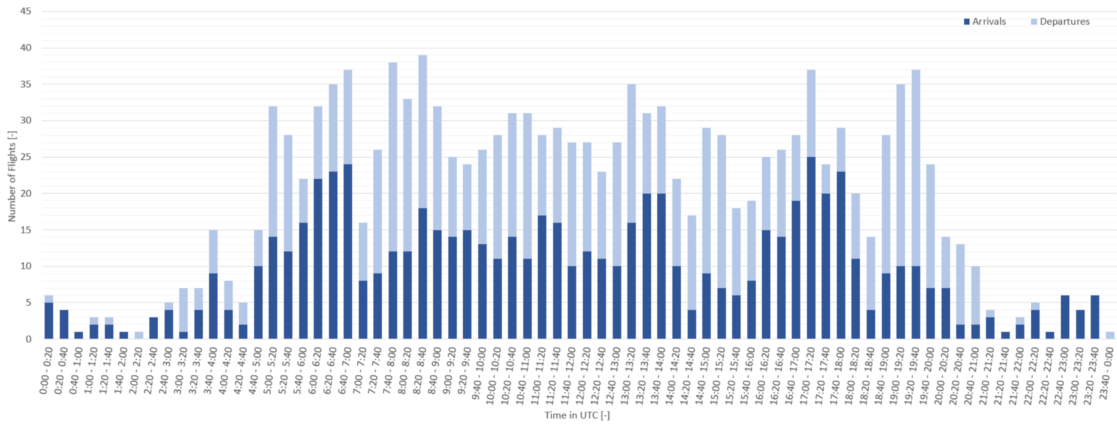


Figure 6.3: Example of distribution of arrivals (dark blue) and departures (light blue) at Schiphol Airport throughout a day

As was shown in Figures 6.2a and 6.2b, the estimated traffic peaks may both increase and decrease with the introduction of XMAN. Currently, Schiphol Airport works with the inbound and outbound peak system. In the inbound peak, quite a few traffic bunches are counted, while during outbound peaks the inbound traffic is substantially lower. So instead of trying to influence the number of traffic bunches using the peak system, the solution may be found in changing the peak system. Instead of applying a peak system, maybe it is better to smoothen the traffic and have a constant amount of inbound and outbound traffic throughout the day. This does bring some challenges, namely the optimisation of runway usage and the effect on connecting flights for airliners, e.g. the Royal Dutch Airlines. The effect of a constant inbound and outbound flow, and thereby a reduction in traffic peaks, should be investigated to see if it is possible to reduce the number of traffic bunches.

Chapter 7

Conclusions

The purpose of this research is to investigate the feasibility of cross-border arrival management (XMAN) for Schiphol Airport in order to influence traffic bunching. The extension of the horizon and the application of a tighter approach margin were investigated to find effects on the low-level delay absorption, arrival sequence stability, flight plan changes and traffic bunches.

In this report, the results are presented and discussed. Using an extension of the current planning horizon, the number of disturbed descents significantly reduces, meaning the sequence is not altered once aircraft start their descent. Next to that, by applying en-route speed changes the low-level delay also significantly decreased, however at the cost of a significant increase in number of sequence changes and number of Scheduled Time of Arrival (STA) revisions. Both the Initial Approach Fix (IAF) accuracy and the inter-arrival time stayed constant throughout the experiment, indicating no influence on the Terminal Manoeuvring Area (TMA) operations when XMAN would be applied. A significant increase is seen in the number of speed changes, mainly before Top Of Descent (TOD). This result is expected as aircraft are now under continuous speed control in the en-route phase. Lastly, no significance was seen when looking at the number of traffic bunches. The number of bunches stayed constant throughout the experiment, implying extending the horizon does not influence this number.

Looking at the results when applying a tighter approach margin, no influence of a tighter approach margin could be seen on the disturbed descents for Arrival Management (AMAN). For XMAN, the results turned out to be inconclusive, due to equal results. A tighter approach margin appeared to have an effect on the low-level delay for AMAN, but post-hoc tests concluded no significant effect. For XMAN, the main test already turned out to be not significant. The number of sequence changes and number of STA revisions appeared not to be significantly affected by a tighter approach margin. The inter-arrival time stayed constant, but a significant increase was seen in IAF accuracy. This increase is related to the fact that two different approach margins are used, and thus the accuracy should indeed increase when using a tighter margin. The number of speed changes shows a significant increase when using a tighter approach margin. This increase is seen both before and after TOD. The reason for this increase is the fact that aircraft will receive speed advisories already when the delay is more than 30 seconds, compared to when the delay is more than 120 seconds. Last but not least, a significant effect is seen in the number of traffic bunches. The reason being that two different Amsterdam (EHAA) Cross Border Airspace (CBAS) margins are used. The analysis using the same EHAA CBAS margin showed no significant effect when applying a tighter approach margin.

So to give an answer to the research question:

To what extent is traffic bunching influenced by the use of cross-border arrival management at Schiphol Airport?

The number of traffic bunches is neither affected by an extension of the horizon, nor by applying a tighter approach margin. Does that mean the use of XMAN does not contribute to the current arrival management system? No, on the contrary, XMAN will help in reducing the low-level delay and thereby optimise the descent phase of flight. The cost of using XMAN is the increase in sequence changes and number of STA revisions, and the increase of speed changes.

Chapter 8

Recommendations

Now that the results have been presented and the conclusions have been drawn, it is time to have a look at what can be done to further improve these results (Section 8.1) and what research can be performed as a result of this study (Section 8.2).

8.1 Improvements

This section gives some improvements that can be done considering the current research.

8.1.1 Sequencer module

As a first improvement to this research, the sequencer may be improved to ensure a more stable sequence. Instead of applying dynamic runway assignment before the start of the simulation, the assignment of the runway should be done when the aircraft crosses the planning horizon. By doing so, it is possible to check the capacity at each runway and decide which runway is available. Next to that, pop-up flights are, in real life, planned manually. The procedure by the Approach Planner is to leave the current sequence intact and assign a landing slot to the pop-up flight at the end of the current sequence. As a result, the Area Control Center (ACC) controllers deem the approach sequence more stable. The effect of applying front-loading should also be researched. Front-loading is to assign a landing slot earlier than the estimated time of arrival. As a result, the aircraft will have negative delays that may be absorbed by flying direct routes or by flying at a higher altitude for a longer period of time. The absorption of negative delays should also be implemented in the AMAN Research Simulator (ARSIM).

8.1.2 Delay threshold

Another improvement is the introduction of a delay threshold. A delay threshold is a minimum amount of delay that an aircraft needs to have before a speed reduction is applied. This threshold does not have to be equal to the approach margin. As an example, for London Heathrow the delay threshold is 10 minutes. Only if the delay is more than 10 minutes, the aircraft receives a speed advisory. The same principle can be applied at Schiphol Airport too. The ideal value of the delay threshold should still be found, but the introduction of the threshold will allow some of the delay to be absorbed by the Dutch ACC controllers. As was seen in the results, some of the delay should still be absorbed at low-level. The Dutch ACC controllers will be able to optimise the approach sequence in Dutch airspace, but at least some of the delay may be absorbed en-route. Next to a delay threshold, the use of discrete speed instructions should be investigated. In the current research, speed advisories were given on a continuous basis. However, air traffic controllers will judge the amount of delay and issue a discrete speed instruction. The implementation of discrete speed instructions in ARSIM should reduce the total number of speed instructions.

8.2 Additional research

Next to the improvements, additional research should be done on different subjects. This section indicates what research could be done.

8.2.1 Speed advisories

Additional research should be done on the number of speed changes issued by surrounding centres and upper centres, such as Maastricht Upper Area Control (MUAC). As an example, MUAC currently handles speed instructions for cross-border arrival management for London Heathrow. The additional speed advisories that should be given for Schiphol Airport will add to the workload and radio telephony (R/T) of MUAC controllers. The increase in workload and R/T should be researched. Since more airports will start to use XMAN in the coming years, the workload and R/T will increase for area controllers in surrounding airspace and upper airspace. Additional research should be performed how the additional workload and R/T for XMAN can be minimised and distributed among other centres.

8.2.2 Schiphol Airport peak system

Another subject for additional research is to evaluate the change of the inbound and outbound peak system to a continuous inbound and outbound flow, where 50% of the aircraft per hour are inbounds and the other 50% are outbounds. As a result, instead of having to deal with 24 inbounds the first twenty minutes and thereafter only 8 inbounds for the next twenty minutes, the traffic can be spread out. As a consequence, a continuous flow of inbound aircraft will be seen. As less aircraft will be arriving in a given time frame, it should help to reduce the number of traffic bunches.

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