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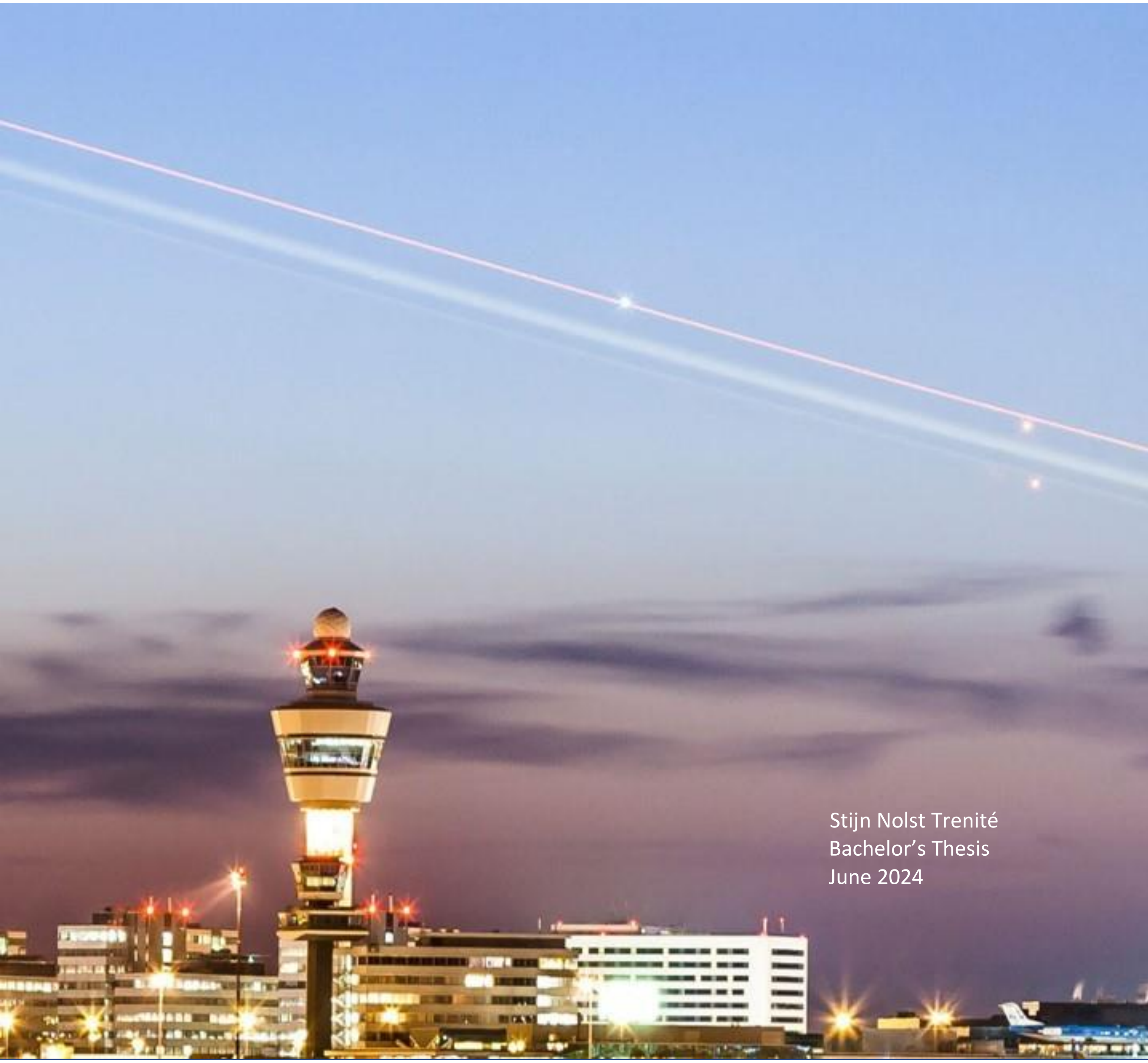
Implementing Required Navigation Performance Authorization Required

The feasibility and achievability of transitioning to a full RNP AR operation at Schiphol Airport



Stijn Nolst Trenité

Bachelor’s Thesis

June 2024

Implementing Required Navigation Performance Authorization Required

The feasibility and achievability of transitioning to a full RNP AR operation at Schiphol Airport

Author
Stijn Nolst Trenité

AUAS Supervisor
Alejandro Murrieta Mendoza

AUAS Department
Faculty of Technology – Aviation Academy

LVNL / KDC Supervisor
Koos Noordeloos

LVNL Department
Performance & Development – Strategy

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I, Stijn Nolst Trenité, hereby declare that this thesis entitled 'Implementing Required Navigation Performance Authorization Required: Feasibility and achievability of transitioning to a full RNP AR operation at Schiphol Airport' is my own work.

Preface

I am pleased to present this bachelor’s thesis on the implementation of Required Navigation Performance Authorization Required approach procedures at Amsterdam Airport Schiphol.

The goal of this thesis is to provide advice to the Knowledge & Development Centre (KDC) and Air Traffic Control the Netherlands (LVNL) on the feasibility and achievability of the transition process to a complete RNP AR operation at Schiphol Airport by constructing a concept of operations including an RNP AR roadmap while maintaining EHAM’s maximum capacity.

I would like to express my gratitude to my LVNL and KDC supervisor Koos Noordeloos, and to my AUAS supervisor Alejandro Murrieta Mendoza, who generously provided their expertise and assistance during my graduation internship.

I hope this thesis will provide a useful source for the KDC, LVNL, their partners and others interested in this research and serve as a starting point for further discussion on this important and current topic.

Stijn Nolst Trenité
Amsterdam, June 2024

Summary

Air Traffic Control the Netherlands (LVNL) provides Air Navigation Services in the Amsterdam FIR (Dutch National Airspace) below 24500 feet. One of the main responsibilities of LVNL is handling all inbound and outbound traffic at Schiphol Airport (EHAM), one of the largest European hubs, consisting of six (single, dual, parallel and converging) runways in multiple wind directions. Arriving traffic at EHAM enters the Amsterdam FIR boundary as an irregular flow. The flights must be navigated into a correctly separated sequence before safe landings can be conducted at EHAM. These approaches are operated according to various IAPs (Instrument Approach Procedures), designed to adapt to different aircraft capabilities and diverse weather conditions. At present, ILS (Instrument Landing System) and RNP (Required Navigation Performance) are the most favoured available approach procedures at EHAM. Required Navigation Performance Authorization Required (RNP AR) is a modern and more advanced variant of RNP, which is not yet implemented at EHAM. LVNL would like to implement RNP AR approach procedures at EHAM because of their positive effect on optimising the efficiency, safety and environmental impact of descents. However, RNP AR approach procedures have different requirements and constraints compared to the current IAPs operated at EHAM. Especially in terms of airspace, airport, air traffic controller, aircraft and flight crew requirements.

The main objective of this research is to provide advice to LVNL and the KDC (Knowledge & Development Centre) on the feasibility and achievability of transitioning to a full RNP AR operation at EHAM. The main objective was achieved by analysing the impact of implementing RNP AR on the airspace capacity at EHAM, examining the capabilities of LVNL and the airlines on transitioning to a full RNP AR operation and the impact of the implementation on their operation, by assessing the exact performance and environmental benefits of RNP AR through simulation, and by constructing a concept of operations (ConOps) and RNP AR roadmap for EHAM.

To assess the impact on the airspace capacity at EHAM when implementing RNP AR, the approach capacity, runway separations, design concerns and visibility conditions at EHAM are assessed. Currently, LNAV, LNAV/VNAV and LPV are available as RNP approaches at EHAM. RNP AR approaches utilise Baro-VNAV, like LNAV/VNAV approaches, which would make RNP AR approaches less optimal than ILS approaches. So, the implementation of RNP AR procedures could have a slightly negative impact on the approach capacity at EHAM. However, mixing RNP AR with ILS procedures is a promising alternative to prevent this. Furthermore, runway offset in RNP AR designs serves as a buffer for separation. Designing RNP AR procedures for parallel operations at EHAM could allow for slightly reduced buffers, thus increasing the capacity at the airport slightly. However, air traffic controllers at LVNL prefer that the runway offset shall not be reduced. Additionally, using RNP AR as the primary approach at EHAM in the future will have the least amount of negative effect on visibility capacity levels because its characteristics are comparable to an ILS approach, which is available over 98% of the time.

To determine the capability of LVNL to transition to a full RNP AR operation at EHAM, separation standards, LVNL's TMA (Terminal Manoeuvring Area) management and the perspective of the air traffic controller are examined. Turbulence separation during the approach influences the operational capacity of LVNL. However, the RECAT-EU wake turbulence separation standards for the current IAPs at EHAM also apply to RNP AR procedures. The introduction of RNP AR approaches decreases aircraft mileage within the TMA. However, this change may result in controllers losing some control, as aircraft will primarily follow FARs (Fixed Arrival Routes), shifting the focus towards speed control as the primary strategy. This transition could potentially lead to capacity reductions. Therefore, system support to assist air traffic controllers in merging aircraft will be crucial for maintaining maximum capacity levels. As control space decreases within the TMA due to the introduction of FARs, a portion of the separation responsibility will shift to the area controllers. Air traffic controllers currently have limited experience with RNP AR approaches. To increase the RNP AR knowledge and skills of air traffic controllers it is vital to implement required training, focusing on mixed-equipment operations and speed control.

To determine the capability of airlines operating at EHAM to transition to a full RNP AR operation, the fleet and flight crew requirements and capabilities are examined. At present, KLM, EasyJet, Transavia and Delta Air Lines are the biggest airlines at EHAM, while the B737-800, E190, A320 and E175 are the most used aircraft at the airport. Between 2017 and 2024 the overall aircraft RNP AR capability at EHAM rose from 10.1% to 21.9%. When looking at the RNP AR fleet capability per airline, KLM is currently around 20% but will be 100% capable in 2028, just like EasyJet. Transavia is already at 100%, just like Delta Air Lines. The total fleet RNP AR capability at EHAM will be around 80% in 2028. Furthermore, appropriate RNP AR flight crew training is essential. Currently, KLM and Transavia flight crew have little experience with RNP AR approach procedures, whereas Delta Air Lines flight crew has lots. Additionally, the KLM RNP AR trials from 2023 indicate that airlines can benefit greatly from RNP AR approach procedures, in terms of fuel, CO_2 and noise reductions.

To evaluate the exact performance and environmental benefits of RNP AR, compared to other relevant IAPs, RNAV, RNP and RNP AR approaches are simulated for runway 18R at EHAM. The flight paths of these approach simulations are based on existing LVNL waypoints and assumed height and speed restrictions. The RNAV (Area Navigation) approach simulation input is partially based on the RNAV night transition for runway 18R at EHAM, while the RNP approach simulation input is partially based on the RNP night transition. The RNP AR approach simulation input is partially based on the KLM RNP AR trials over the North Sea Canal in 2023. The total distances of the RNAV, RNP and RNP AR approach simulations are 63.2 NM, 63.0 NM and 50.6 NM respectively. This results in a fuel consumption for the B737-800 of 341.09 kg, 340.8 kg and 273.7 kg in the same order. Which leads to a total of 918.3 kg CO_2 emissions for the RNAV approach, 915.4 kg CO_2 emissions for the RNP approach and only 735.2 kg CO_2 emissions for the RNP AR approach.

To finalise the research and visualise the end goal, a concept of operations is constructed, including an RNP AR roadmap for EHAM. The three implementation requirements for RNP AR and EoR (Established on RNP) operations at EHAM are FARs, CDOs (Continuous Descent Operations) and separation-independent operations. These and other relevant requirements for the stakeholders are all achievable within the proposed timeframe, based on the airspace, airport, ATC and airline analyses. Furthermore, a main aspect of the achievability of RNP AR operations at EHAM is upholding the airport and airspace capacity at maximum levels, which is expected to be achievable. Finally, the most suitable starting point of the RNP AR roadmap for EHAM is runway 18R, which is the most used parallel runway at the airport. After which RNP AR should be implemented at runway 18C. The development of the RNP AR roadmap is split into two equal phases. The first phase includes the implementation of RNP AR approach procedures at runways 18R, 18C and 06, with an implementation and evaluation timeline of two years per runway. The second phase includes runways 36R, 36C and 27, with a comparable implementation and evaluation timeline.

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List of Abbreviations

Abbreviation	Definition
ANP	Aircraft Noise and Performance
AR	Authorization Required
ARR	Arrivals
A RNP	Advanced Required Navigation Performance
ATC	Air Traffic Control
ATM	Air Traffic Management
AUAS	Amsterdam University of Applied Sciences
BZO	Limited Visibility Conditions (translated)
CDO	Continuous Descent Operation
CFIT	Controlled Flight Into Terrain
CNS	Communication Navigation & Surveillance
ConOps	Concept of Operations
CTR	Control Zone
dB	Decibel
DEP	Departures
DH / DA	Decision Height / Decision Altitude
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
EHAM	Amsterdam Airport Schiphol
EoR	Established on RNP
FAF	Final Approach Fix
FAR	Fixed Arrival Route
FIR	Flight Information Region
FL	Flight Level
FMS	Flight Monitoring System
ft	feet
FOSA	Flight Operational Safety Assessment
GNSS	Global Navigation Satellite System
I&W	Infrastructure & Water Management (translated)
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules

Abbreviation	Definition
iLabs	Innovation Labs
ILS	Instrument Landing System
ILT	The Human Environment and Transport Inspectorate (translated)
KDC	Knowledge & Development Centre Mainport Schiphol
KLM	Royal Dutch Airlines (translated)
kts	knots
LNAV	Lateral Navigation
LOC	Localizer
LPV	Localizer Performance with Vertical Guidance
LVNL	Air Traffic Control the Netherlands (translated)
MOC	Minimal Obstacle Clearance
NM	Nautical Mile
OBPMA	Onboard Performance Monitoring and Assessment
OCH	Obstacle Clearance Height
OCS	Obstacle Clearance Surface
PBN	Performance Based Navigation
RECAT-EU	European Wake Turbulence Re-Categorisation
RF	Radius to Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RNP AR	Required Navigation Performance Authorization Required
RVR	Runway Visual Range
RWY	Runway
SBAS	Satellite-Based Augmentation System
THRE	Threshold
TMA	Terminal Manoeuvring Area
VNAV	Vertical Navigation

1. Introduction

This chapter will introduce the study and will elaborate on the background information (1.1), the problem statement (1.2), the main research objective and questions (1.3), the sub-objectives (1.4) and the scope and limits (1.5) of this research.

1.1 Background Information

Airspace around airports faces various volumes of air traffic passing through during the day. The airspace around Amsterdam Schiphol Airport is especially congested during peak hours, which are periods with high amounts of traffic going through the airport TMA (Terminal Manoeuvring Area) and happen multiple times throughout the day (Ministry of I&W, 2021). It is crucial to effectively use appropriate navigation systems to prevent the inefficient use of available airspace and keep Schiphol Airport’s runway capacity at maximum possible levels. Currently, almost all air traffic arriving at Schiphol Airport operates according to Performance Based Navigation (PBN). PBN is a collective term for navigation procedures which rely on advanced navigation systems. At Schiphol Airport, most arriving aircraft operate according to Required Navigation Performance (RNP), which is a modern, commonly used variant of PBN (Moving Dot, 2020). Schiphol Airport will from now on be called by its ICAO code, EHAM.

However, RPN was introduced over 25 years ago and meanwhile, more advanced navigation systems and corresponding procedures have allowed flight crew to operate more efficiently and more environmentally friendly than when using RNP. An innovative variant of RNP is Required Navigation Performance Authorization Required (RNP AR), which was pioneered in 2011. (Boeing, 2011) RNP AR is a set of procedures which enable aircraft to operate on a more desirable flight path during an approach, thereby improving the use of the available airspace. Onboard RNP AR equipment provides flight crew with navigation capabilities to fly along a more precise flight path with exceptional accuracy and integrity. The RNP AR procedures followed by the system allow aircraft to fly curved legs in the final approach instead of point-to-point, like with RNP. This could reduce the total track miles per flight during the final approach (Miller & Bruce, 2011). RNP AR also allows flying within a smaller corridor as RNP, as will be explained further on.

Next to providing smaller corridors, RNP AR procedures also allow for a smaller obstacle clearance surface (OCS) around the approaching aircraft, which permits aircraft to fly closer to surrounding objects during the final approach, making the system ideal for approaches in an environment with challenging weather or terrain. Modern RNP AR procedures have a width ranging from 0.2 to 2 NM, which is smaller than the minimum obstacle clearance (MOC) of RNP procedures, which is 2.5 NM (ICAO, 2023).

Because the RNP AR procedures reduce the number of track miles per approach and allow for more precise corrections compared to older procedures, the system has a positive environmental impact on the operation. This means that the procedures of RNP AR could provide a reduction in the amount of carbon emissions and noise nuisance for local residents of EHAM (Guo & Huang, 2020).

Because of the potential benefits of RNP AR, Air Traffic Control the Netherlands (LVNL) would like to implement the approach procedures in the entire operation at EHAM. Currently, none of the approaches at EHAM are being performed using RNP AR. In the future, LVNL would like all air traffic at EHAM to operate according to RNP AR procedures. As they might increase the airspace capacity at EHAM and provide the airport with a constant runway capacity (Unkelbach & Dautermann, 2021).

1.2 Problem Statement

RNP AR is a relatively new navigation system operating according to an innovative set of approach procedures. Currently, none of the flights arriving at EHAM operate according to RNP AR procedures (LVNL, 2024). In the near future, LVNL would like all incoming flights at EHAM to operate according to these procedures. However, the transition from RNP to full RNP AR faces several requirements, challenges and constraints. RNP AR operates according to different requirements than RNP. So, the RNP AR navigation system has different air traffic control operating requirements than normal RNP procedures (McDonald & Kendrick, 2008). It needs to be investigated if EHAM and LVNL are currently operating according to these requirements. For EHAM in terms of its runway characteristics and operational capabilities and for LVNL in terms of aircraft separation, sequencing and air traffic controller requirements. It needs to be assessed if operational changes are needed for these stakeholders to adapt to the full implementation of RNP AR.

The problem that this research addresses is determining the feasibility and achievability of transitioning to a full RNP AR operation at EHAM while maintaining maximum capacity levels. Currently, it is unknown if switching to a full RNP AR operation is feasible and achievable for the major stakeholders: the airport (EHAM), air traffic control (LVNL) and the airlines. It is also unknown if these stakeholders have the capacity to switch to RNP AR in a reasonable timeframe. Besides considering the operational requirements for EHAM and LVNL for a transition to a full RNP AR operation, it is also crucial to take into account the airline requirements in terms of flight crew training and fleet structure. RNP AR has distinct aircraft and flight crew requirements, compared to RNP (Entzinger, Nijenhuis, Uemura & Suzuki, 2013). It is essential to look at the fleet renewal strategy of the largest airlines operating at EHAM, with the most focus on KDC partner KLM. Additionally, the possibility of installing RNP AR systems into aircraft of the current fleet needs investigation.

A thorough analysis of transitioning to a full RNP AR operation at EHAM needs to be performed to investigate the feasibility and achievability of this implementation. A concept of operations (ConOps) for the transition to a complete RNP AR operation at EHAM needs to be constructed, based on relevant airspace, airport, capacity, ATC and airline analyses. Furthermore, to give the stakeholders a better understanding of a possible implementation timeline, a guidance roadmap on the transition to RNP AR needs to be developed. Without this research, the stakeholders would not have clarity about the feasibility and achievability of transitioning to a completely RNP AR operation at EHAM, resulting in not knowing if their future strategies will align with the operation at EHAM.

1.3 Research Objective & Questions

This research is carried out for Air Traffic Control the Netherlands (LVNL) and the Knowledge & Development Centre Mainport Schiphol (KDC). With the problem statement and the expectations and interests of LVNL and the KDC in mind, the following main research objective has been formulated:

'Determine the feasibility and achievability of transitioning to a full RNP AR operation at EHAM while maintaining maximum capacity, by constructing a concept of operations including an RNP AR roadmap, based on relevant airspace, airport, capacity, ATC and airline analyses.'

Achieving the main research objective is supported by answering the following research questions:

1. What is the impact of implementing RNP AR approach procedures on the airspace capacity at EHAM?
2. How capable are LVNL and the airlines of transitioning to a full RNP AR operation at EHAM and what impact will the implementation have on their operation?
3. What are the exact performance and environmental benefits of RNP AR, compared to the other IAPs?
4. What implementation steps are needed and what would be the most suitable roadmap to follow for the stakeholders during the RNP AR implementation process at EHAM?

1.4 Sub-Objectives

Based on the main objective and the research questions, the following sub-objectives have been formulated:

1. Assess the impact of an RNP AR implementation on the airspace capacity at EHAM by performing an airspace analysis and airport analysis, including relevant airspace, airport and capacity characteristics.

2. Determine the capabilities of LVNL and the airlines operating at EHAM on transitioning to a full RNP AR operation and the impact of the implementation on their operation, by performing an ATC and airline analysis, including the requirements and experience of air traffic controllers, aircraft and flight crew.

3. Assess the exact performance and environmental benefits of RNP AR approaches, compared to the other relevant IAPs at EHAM by simulating RNAV, RNP and RNP AR approach procedures for runway 18R at EHAM.

4. Construct a concept of operations for the transition to a full RNP AR operation at EHAM, including appropriate implementation steps and a structured RNP AR roadmap.

1.5 Scope and Limits

This study consists of four research areas, equivalent to the four sub-objectives. The first research area consists of an airspace analysis, an airport analysis and an airspace capacity assessment. In the airspace analysis, the airspace characteristics of EHAM are determined, including the variety of instrument approach procedures at EHAM. Also, there is elaborated on the mixed traffic separation within the airspace of EHAM. Furthermore, in the airport analysis, the runway characteristics of EHAM are assessed, including the parallel runway operations at the airport. Additionally, the difference in airspace capacity at EHAM after transitioning to a full RNP AR operation is determined. This is done by analysing the approach capacity, runway separation, relevant design concerns and visibility conditions.

The second research area contains an assessment of the capabilities of LVNL and the airlines operating at EHAM on transitioning to a full RNP AR operation and the impact of the implementation on their operation. The capabilities of and impact on air traffic control are determined by investigating separation standards at EHAM, the current TMA management of LVNL and the experience and knowledge perspective of the air traffic controller. The capabilities of and impact on the airlines are assessed by analysing airline operations at EHAM, the RNP AR requirements of relevant aircraft, current fleet development and the experience and knowledge perspective of the flight crew. Finally, some important operational and environmental considerations for airlines are discussed.

The third research area includes RNAV, RNP and RNP AR approach simulations for runway 18R at EHAM, to assess the exact performance and environmental benefits of RNP AR approaches, compared to the other relevant IAPs at EHAM. The approach performance is measured by analysing pre-determined waypoints and their effect on the total track miles. The environmental benefits are assessed by delving deeper into the effect of RNP AR approaches on CO_2 emissions and noise pollution.

The fourth research area involves the construction of a ConOps for EHAM on transitioning to a full RNP AR operation. The implementation steps and achievability of the ConOps are defined by analysing the implementation requirements for RNP AR operations and the achievability of the end goal. Additionally, a structured RNP AR roadmap for EHAM provides the airport with the necessary information on the beginning and development of the several RNP AR implementation phases at EHAM.

2. Theoretical Framework & Literature Review

The following chapter contains the theoretical framework (2.1) and the literature review (2.2).

2.1 Theoretical Framework

The PBN Concept

The Performance Based Navigation (PBN) concept is a framework for optimising air traffic navigation by integrating three core components: navigation specification, navigation infrastructure, and navigation application. The PBN Concept, alongside communication, surveillance, and ATM systems and procedures, forms the airspace concept (EUROCONTROL, n.d.). Figure 2.1.1 shows an overview of the entire airspace concept, including the PBN concept.

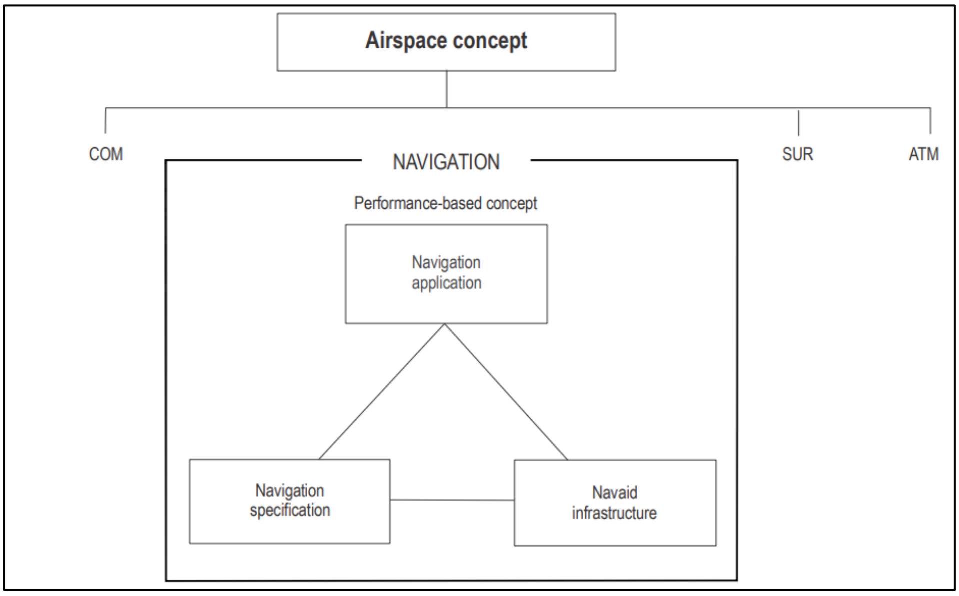

Figure 2.1.1: The Performance-based navigation concept within the Airspace Concept (ICAO, 2023)

The navigation specification of PBN defines the required performance and functionalities for area navigation equipment, flight crew, and avionics. This specification ensures accurate and continuous path following along designated routes or procedures and identifies which navigation sensors are necessary to meet operational needs. The navigation infrastructure of PBN encompasses both ground- and space-based navigation aids that provide the aircraft systems with range and dimensional data. This data is then processed to compute a position that meets the accuracy requirements of the navigation specification. The navigation application of PBN translates the airspace concept's operational needs into actual routes and instrument flight procedures (IFPs), each with specific navigation performance requirements to ensure optimal efficiency and safety within the designated airspace (EUROCONTROL, n.d.).

Laws & Regulations

The main reason for the implementation of PBN would be stricter laws and regulations and future goals on safety, efficiency, predictability, environment and accessibility. Regulations on PBN are issued by various organisations on different regional, national, European or international levels. For EHAM, ICAO, the European Commission and national authorities regulate most issues around PBN.

The following relevant examples show that these organisations prioritise the implementation of PBN. The Global Aviation Navigation Plan, which is supported by the Dutch government and the Ministry of I&W, describes PBN as their highest priority (ICAO, 2016). ICAO sees the implementation of PBN as a key enabler for advanced air traffic operations and assists countries in the implementation of PBN. Doc 9613 provides the background and detailed technical information required for operational implementation planning and a large set of navigation applications (ICAO, 2023). Furthermore, the European Commission has agreed on the PBN Implementing Regulation, which aims to answer ICAO's GANP (European Union, 2018). Also, the Dutch authorities have implemented the "Regeling boorduitrusting" 8, which is a national regulation that requires aircraft flying at certain flight levels to be equipped with specific PBN navigation equipment (I&W, 2020).

Navigation Specifications

The PBN navigation specification categorises aircraft equipage and avionics into two types: Area Navigation (RNAV) and Required Navigation Performance (RNP), which are distinguished by the presence of Onboard Performance Monitoring and Assessment (OBPMA) functionality, typically provided by GPS (EUROCONTROL, n.d.). Currently, the primary difference is aircraft age. Pre-2000 aircraft, equipped with older avionics, often lack the comprehensive capabilities of their modern counterparts and thus often fall under the RNAV classification. Post-2000 aircraft with more advanced avionics and GPS capabilities often qualify as RNP compliant. A comparison between the flight paths of conventional, RNAV and RNP approach procedures is shown in Figure 2.1.2.

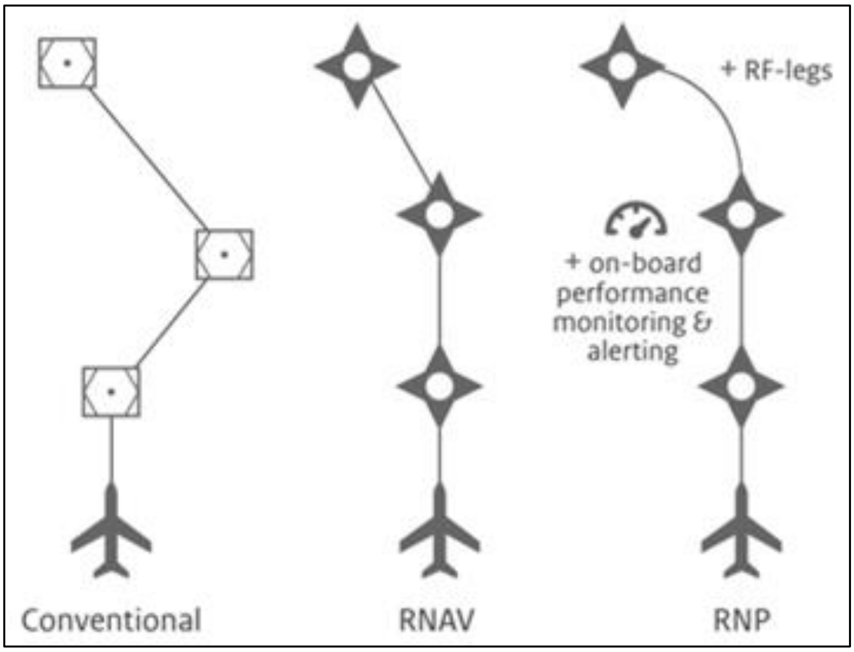

Figure 2.1.2: Comparison between conventional (left), RNAV (middle), and RNP (right) flight paths. (Moving Dot, 2020)

With the introduction of new RNAV and RNP navigation specifications over the past decades, the more accurate and efficient they became. For example, the first RNAV specification was RNAV 10. This specification mandated a lateral navigation performance of 10 nautical miles for at least 95% of the flight time. This level of accuracy was sufficient to support a separation standard of 50 nautical miles laterally and longitudinally. In contrast, the expected performance of the first RNP approach procedure is 1 NM of accuracy in the initial and intermediate phases of the approach and 0.3 NM of accuracy in the final approach phase, 95% of the flight time (ICAO, 2023).

RNP AR Characteristics

A relatively new and modern navigation specification variant within RNP is RNP AR (Required Navigation Performance Authorization Required). RNP AR approach procedures use advanced onboard navigation systems to enable highly accurate instrument approaches. Qualified aircraft equipped with these systems meet stringent performance criteria for navigation precision, monitoring, and alerting, ensuring safe and efficient arrival at airports even in challenging environments where normal RNP approaches may be restricted or more difficult to perform (I&W, 2021). RNP is a standard for an aircraft's navigational accuracy and its ability to maintain a designated path.

RNP AR approaches further enhance this concept by specifying the precise navigation performance demanded for both lateral and vertical guidance throughout the approach and missed approach procedures. To ensure the safety and effectiveness of these procedures, RNP AR implementation requires specific authorisation from the relevant aviation authority. This authorisation process verifies that the operator, aircraft, and crew possess the necessary capabilities, equipment, and training to navigate within the stringent parameters of an RNP AR approach (MovingDot, 2020). The major differences in flight paths between normal RPN approaches, RNP AR approaches with challenging terrain and RNP AR approaches which allow a shorter runway line-up are shown in Figure 2.1.3, from left to right.

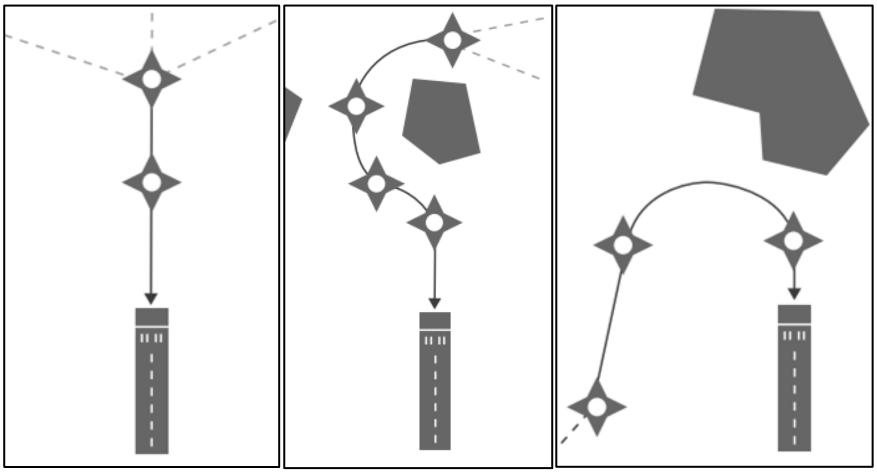

Figure 2.1.3: RNP approach (left), RNP AR approach with challenging terrain (middle) & RNP AR approach with shorter runway line-up (right) (I&W, 2021)

RNP AR approaches offer a variable but high level of strictness in lateral navigation performance, ranging from 1 NM to a highly precise 0.1 NM (EUROCONTROL, n.d.). While tighter tolerances enable approaches in environmentally complex areas, they demand more advanced onboard navigation systems. This limits the amount of compatible aircraft and potentially increases airline operational costs during the approach. The RNP AR navigation accuracy requirements per approach segment can be seen in table 2.1.1.

Segment	Maximum	Minimum
Initial	1	0.1
Intermediate	1	0.1
Final	0.3	0.1
Missed Approach	1.0	0.1

Table 2.1.1: RNP AR navigation accuracy requirements in NM per approach segment (ICAO, 2021)

RNP AR approaches modernise instrument approaches by delivering high-precision lateral and vertical guidance (3D), enabling more accurate flight paths. This capability allows approaches in areas with challenging terrain, obstacles, or limited ground-based navigation infrastructure. The vertical guidance of RNP AR relies on Baro-VNAV (MovingDot, 2024). This navigation system requires barometric altimeter settings at the airport when approaching using RNP AR procedures. This ensures optimal safety and accuracy during the instrument approach and landing. Figure 2.1.4 shows the lateral guidance of RNP AR from a plan perspective and the vertical guidance of RNP AR from a cross-section perspective. Both lateral and vertical guidance have a minimum obstacle clearance (MOC) of 2RNP on each side of the aircraft, which equals 2NM per side (ICAO, 2021).

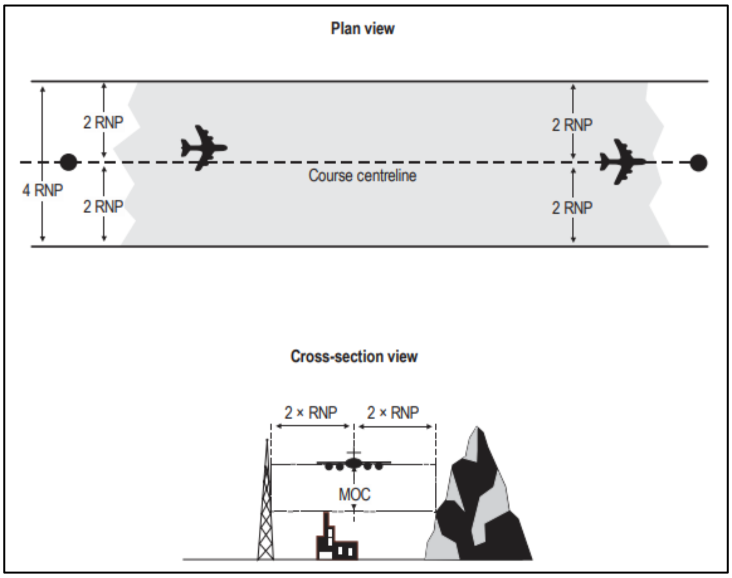

Figure 2.1.4: RNP AR segment widths from a plan view and cross-section view (ICAO, 2021)

RNP AR approaches provide increased navigational accuracy and integrity to unlock greater flexibility in procedure design. This translates to significant advantages, such as the ability to integrate Radius-to-Fix (RF) legs (curved legs) within the final approach segment. An RF leg is a constant radius circular flight path around a turning centre that ends at a Fix (ICAO, 2021). These RF legs enable 3D RNP AR instrument approaches in areas where conventional or RNAV procedures are restricted by terrain, obstacles, or airspace limitations. Figure 2.1.5 shows an example of an RF leg during the final approach segment of an RNP approach. The RF leg enables aircraft to earlier line up with the runway, not having to cross the Final Approach Fix (FAF) of normal RNP approach procedures (ICAO, 2023). This shortcut saves on track miles and thus on fuel.

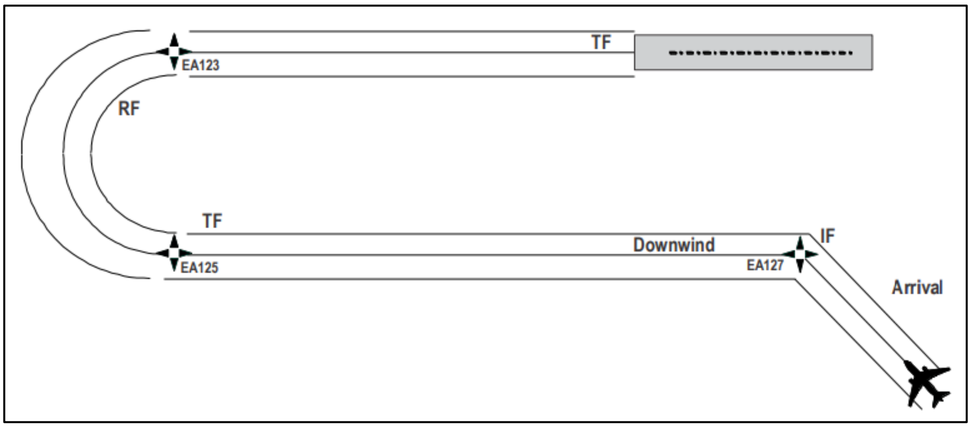

Figure: 2.1.5: RF leg during RNP AR final approach segment (ICAO, 2023)

RNP AR approaches require at least the following three advanced onboard avionic systems to operate: an RNAV system, Global Navigation Satellite System (GNSS) receivers, and the Flight Management System (FMS) (MovingDot, 2024). GNSS forms the primary navigation infrastructure for RNP AR. RNP AR implementation does not require specific communication or air traffic surveillance requirements beyond those for standard RNP approaches. However, to ensure safety and accuracy during the barometric vertical navigation guidance of RNP AR, both a local altimeter setting for the flight crew and its availability at the destination airport are crucial.

Established on RNP AR

RNP AR approaches can also be used to support independent parallel approach operations. Independent parallel approaches are a method for achieving simultaneous landings on nearby runways without relying on separation minima established by air traffic control through surveillance systems and represent a significant advancement in maximising runway capacity (ICAO, 2020). RNP AR approach procedures are one of the few procedures that allow this. Simultaneous parallel approaches may be performed to parallel runways using any combination of 3D instrument approach procedures. One of those combinations is RNP AR approach procedures combined with "Established on RNP AR" (EoR) (ICAO, 2016). Figure 2.1.6 shows an example of independent simultaneous EoR approaches on parallel runways.

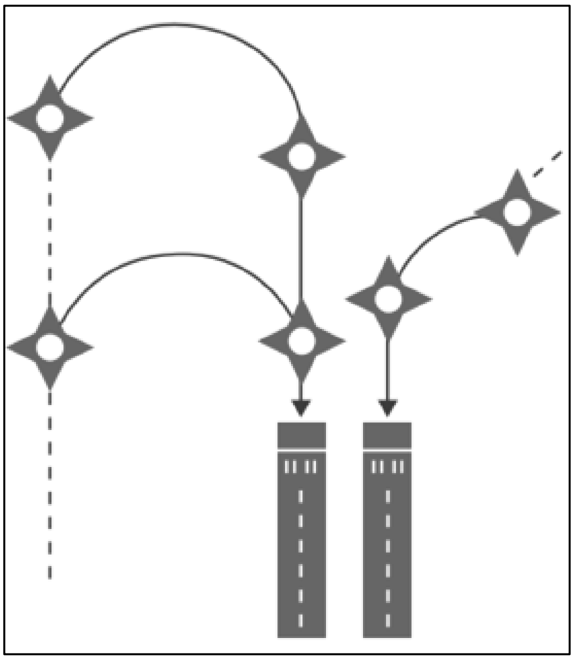

Figure 2.1.6: Independent parallel Established on RNP AR approaches (I&W, 2021)

An aircraft operating an RNP AR approach procedure is considered to be established for the approach procedure if it meets the following demands. The aircraft must confirm that it is established on the RNP AR approach procedure before an authorities-designated point, and this designated point must be located on the RNP AR approach path to ensure the appropriate horizontal separation minimum of 3NM from the neighbouring parallel approach procedure (ICAO, 2016).

Current RNP AR regulations determine specific combinations of 3D instrument approach procedures for parallel runway operations. To enable EoR operations, one runway must have a designated RNP AR approach, while the other runway can utilise either an RNP AR, a standard RNP, or an ILS approach (ICAO, 2020). Notably, EoR standards are not yet defined for scenarios involving any other combinations of approach procedures on parallel runways.

2.2 Literature Review

RNP AR is a relatively new and unknown navigation system which operates according to a complex set of precise procedures. However, various studies have investigated several relevant aspects of the topic. Over the last decades, PBN systems have taken over the navigational tasks of conventional air navigation. Guo and Huang (2020) showed the operational advantages of PBN over conventional navigation, including the major differences between RNP AR and RNAV. The results of the experiments showed RNP procedures offer shorter routes and lower fuel use for airports with difficult terrain, obstacles, and limited navigation aids. While PBN routes in flat areas with plenty of navaids might not be shorter than traditional routes, they can still improve ATC efficiency by increasing airspace capacity. It represents the direction of navigation and offers a reliable path to improve overall safety, operational efficiency, and workload reduction for both pilots and controllers.

The implementation of modern PBN systems like RNP AR comes with challenges. Unkelbach and Dautermann (2021) developed a new RNP AR approach for a runway at Isa Air Base, Bahrain, addressing two of these critical challenges. Curved segments within the final approach allow for adjustments, keeping aircraft clear of a neighbouring airbase's control zone even during descent. Additionally, the approach requires high navigational accuracy (RNP 0.1) throughout, ensuring a safe path in bad weather. This was confirmed by extensive testing in a full-flight simulator where extreme weather conditions were simulated. Despite these challenges, the required navigational accuracy was achieved without compromising other flight parameters. Test flights further confirmed the approach's practicality in real-world scenarios.

RNP AR provides multiple benefits compared to older navigation systems, especially at airports with specific constraints. McDonald and Kendrick (2008) illustrated the significant improvement in capacity achieved through the integration of GPS systems in low RNP AR operations at airports facing terrain-related challenges. The study concentrated on RNP AR availability at four airports known for their challenging terrain, Linzhi, Queenstown, Aspen and Quito. An analysis was conducted using simulations with terrain data under normal GPS conditions and assessed that there is a high impact on the airport and airspace availability during satellite outages. Both simulations and real-world tests demonstrate that RNP AR surpasses GPS receivers in accuracy, even under ideal conditions. Additionally, RNP AR exhibits significantly greater resilience when faced with weak satellite configurations.

When transitioning to a new navigation system with more stringent requirements, like RNP AR, it is crucial to perform a safety assessment of the transition. Savas and Sahin (2017) investigated RNP AR procedures as a potential solution for mitigating Controlled Flight Into Terrain (CFIT) accidents. Additionally, the Flight Operational Safety Assessment (FOSA) methodology was evaluated. FOSA served as a crucial part of the authorisation process for RNP AR procedures, offering a means of evaluating specific scenarios and serving as a valuable tool for mitigating the risk of CFIT occurrences. CFIT accidents often involve loss of control, situational awareness, and deviation from the planned path. RNP AR Approach procedures offered a significant solution by enhancing pilot situational awareness and improving aircraft monitoring and control during the critical approach phase. Furthermore, the FOSA can be employed alongside RNP AR to provide a safety level equivalent to traditional ILS.

Various navigation procedures have different amount of crew demands. Entzinger, Nijenhuis, Uemura and Suzuki (2013) studied the mental demands of curved approaches compared to straight approaches. Physiological measures, control inputs, and pilot performance were used to assess the relative complexity and potential risks of automation in standard and challenging conditions. It was concluded that having enough time is crucial for the pilot to stabilise the aircraft during the approach. This can be more difficult when operating curved approaches in the final approach segment, because of insufficient time to make corrections compared to operating straight approaches. With highly automated approach operations, like RNP AR, mitigation of risks is crucial for a safe approach.

An important characteristic of RNP AR procedures is the allowance of Radius to Fix (RF) legs during the final approach. Miller and Bruce (2011) analysed RF legs and their integration into instrument procedure designs, such as RNP AR. The study also described the advantages added by both present and future air transportation systems when RF legs are accessible across all aviation sectors, such as improved consistency, reliability, and predictability while turning. Significant cost reductions for airlines across all segments, including flight time, fuel, maintenance, and crew expenses, could be achieved by implementing direct routing and minimising vectoring, leading to substantial efficiency gains.

The main benefit of EoR under RNP AR approaches is the possibility of independent parallel approaches. Hanses and Korn (2015) studied a parallel approach procedure design which includes RNP AR design constraints. To enable independent operations for segmented approaches at airports with parallel runways, a safety concept is described, leveraging a combination of a traditional straight ILS approach and a segmented RNP AR approach. Given the availability of RNP AR for segmented approaches, this concept proposed a pathway to implement noise-reducing and capacity-boosting routing at major hub airports with sufficiently spaced parallel runways. It was concluded that RNP AR allows for more flexible independent parallel procedures, including stricter separation between aircraft during the final approach.
Furthermore, when looking at independent parallel RNP AR operations, it is also important to look at possible mixed procedures. Amai and Matsuoka (2015) conducted an experiment to find the procedure which makes the safest mixed operation of RNP AR approach procedures and other approach procedures. The feasibility of mixed operations was studied, involving aircraft operating according to RNP AR approach procedures and those using ILS approach procedures, while both aircraft are using the same runway at an airport without parallel runways. An ATC real-time simulation revealed that "first come, first served" is inapplicable in mixed-traffic environments. The impact of varying mixing rates on controller workload was not conclusive due to individual air traffic controller differences.

RNP AR procedures present multiple environmental benefits compared to older navigation variants in terms of track miles, carbon emissions and noise pollution. Morscheck (2018) claimed that RNP AR approaches reduce noise nuisance for local residents around airports. The paper introduced an automated technique aimed at optimizing Advanced RNP (A RNP) and RNP AR approaches and focuses on refining approach procedures to lighten noise disturbances affecting residential areas near airports. While the results of the new RNP AR and A RNP approaches show effectively reduced overall noise pollution for local residents, it is important to recognise that the final approach remains the most impactful noise source for communities.
Additionally, Morscheck (2020) emphasised the significance of the density of inhabited regions in determining the noise advantages of A RNP and RNP AR. It states that low population density reduces potential savings as there are no residents to avoid, while high density poses challenges as there's limited room to divert flight paths. The majority of noise-related disturbances occurred during the final approach segments. Therefore, the population near the runway have the highest possible noise nuisance risk.

To be able to understand the possibilities if transitioning to a full RNP AR operation at EHAM, it is crucial to investigate other airports which already have implemented the system. Medeiros, Silva and Kousson (2012) studied the feasibility of using RNP AR approach procedures at Pico Island Airport in the Azores. This study demonstrated that new RNP AR procedures significantly enhance airport operability while having minimal installation and maintenance costs compared to conventional equipment. It was concluded that the inherent advantages of implementing these procedures alongside RNP navigation systems far outweigh any potential drawbacks.

The aforementioned literature encompasses ideas related to PBN and RNP AR, such as the challenges and benefits of the navigation systems and their procedures. However, none cover the thought of transitioning to a full RNP AR operation at EHAM or any other related or comparable airport.

3. Methodology

This chapter discusses the methodological approach (3.1), and the methodologies of the research objectives (3.2-3.5). This research is performed using various research methods, both qualitative and quantitative.

3.1 Methodological Approach

The main objective of this research is to determine the feasibility and achievability of transitioning to a full RNP AR operation at EHAM while maintaining maximum capacity, by constructing a concept of operations including an RNP AR roadmap, based on relevant airspace, airport, ATC and airline analyses. To accomplish this main research objective, a structured methodological approach is needed. Figure 3.1.1 shows the overall methodological approach of this research, including all sub-objectives.

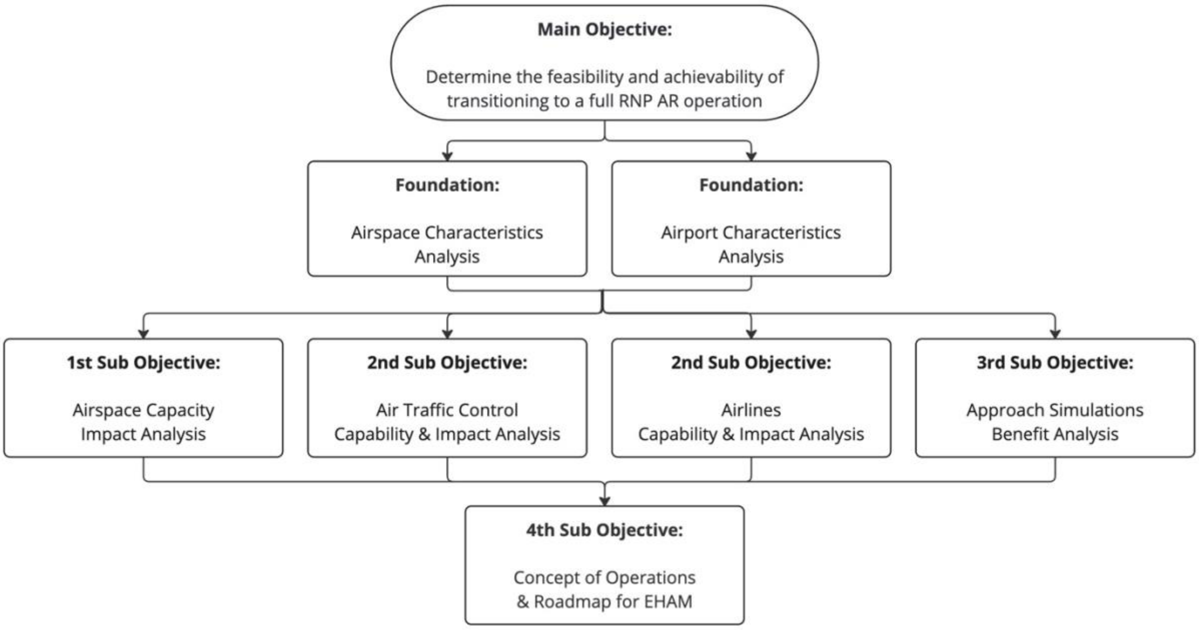

Figure 3.1.1: Overall methodological approach of this research including all sub-objectives

The airspace and airport characteristics analyses form the foundation of this research. These analyses contain all the relevant information needed to achieve all sub-objectives. The first sub-objective is assessing the impact of an RNP AR implementation on the airspace capacity at EHAM, which is achieved by performing an airspace capacity analysis. The second sub-objective is determining the capabilities of LVNL and the airlines operating at EHAM on transitioning to a full RNP AR operation and the impact of the implementation on their operation, which is achieved by performing ATC and airline capability and impact analyses. The third sub-objective is assessing the exact performance and environmental benefits of RNP AR approaches, compared to the other relevant IAPs at EHAM. This is achieved by simulating RNAV, RNP and RNP AR approach procedures for runway 18R at EHAM. The fourth sub-objective is constructing a concept of operations for the transition to a full RNP AR operation at EHAM, including appropriate implementation steps and a structured RNP AR roadmap, which is achieved by combining and using the results from the first, second and third sub-objective. The following sub-chapters will elaborate on the steps taken to perform these analyses, shown in Figure 3.1.1.

3.2 Airspace, Airport & Capacity Analyses

The results section that achieves the first sub-objective (4.1) consists of three subsections: the airspace analysis, the airport analysis and the airspace capacity analysis. The steps taken to perform these analyses are described.

The first foundational part of this thesis is the airspace analysis, which consists of the next four steps.

1. Quantitative data is gathered on the airspace characteristics and traffic volumes of EHAM by analysing the annual traffic reports of Schiphol Group and the air traffic management of LVNL.
2. The structure of the Amsterdam Flight Information Region (FIR) is investigated by identifying its Initial Approach Fixes (IAFs), ARTIP, RIVER and SUGOL, and their corresponding origins and traffic distribution.
3. An assessment of the availability of instrument approach procedures in the EHAM airspace is performed, including the absence of RNP AR approach procedures, by examining the current air traffic handling of LVNL during daytime and nighttime operations.
4. The current constraints regarding handling mixed-equipped traffic at EHAM are analysed by reviewing the differences in the protection areas of RNAV, RNP, and RNP AR approaches based on ICAO regulations and by examining the different lateral accuracy requirements for RNP and RNP AR procedures across different flight phases based on EUROCONTROL standards.

The second foundational part of this thesis is the airport analysis, which consists of the next four steps.

1. Relevant data is compiled on the runway characteristics and usage of EHAM. The runway characteristics, usage and capacity at EHAM are assessed by analysing operational data of Schiphol Group, including availability schedules and spatial and environmental constraints affecting runway operations. By doing this, specific runways which are closed during certain parts of the day or night, and the effect on overall airport operations, can be identified.
2. An assessment of the available IAPs for each runway is performed by examining recent FlightAware® IAP data of EHAM.
3. Historical runway utilization data of LVNL between 2018 and 2023 is reviewed to conclude runway traffic distribution patterns.
4. The parallel runway operation at EHAM is analysed by examining traffic handling data of LVNL between 2018 and 2023, focussing on the most frequently used runway combinations at EHAM.

To evaluate the impact of the implementation of RNP AR approach procedures on the current airspace capacity at EHAM, the following five steps are taken.

1. To estimate the current approach capacity at EHAM, data is gathered on different RNP approaches, including their Decision Height (DH) and Obstacle Clearance Heights (OCH) by analysing relevant ICAO regulations. By comparing the DH and OCH values for RNP and ILS approaches, ILS approach data from the eAIP is collected for runway 18R. By using these analyses, a conclusion can be drawn on the operational impact of RNP AR approaches on the airspace capacity at EHAM.
2. To analyse and evaluate the impact of RNP AR approach procedures on runway separation requirements at EHAM, runway offset data from LVNL is used.
3. To further evaluate the runway separation at EHAM, runway data and relevant design concerns are examined. When looking at these design concerns, information on potential design issues is collected by analysing day- and night-time operations at EHAM regarding current parallel approaches.
4. To evaluate the impact of RNP AR approaches on the airspace capacity at EHAM regarding local visibility conditions, the BZO (Limited Visibility Condition) phases with their corresponding runway visual range (RVR) and cloud ceiling conditions at EHAM are used.
5. To gather information on EHAM's low visibility procedures and their impact on airport capacity, historical LVNL traffic data between 2016 and 2023 is analysed. By using this traffic data, the frequency and distribution of different visibility conditions at EHAM are concluded and linked to the feasibility and capacity impact of RNP AR approaches.

3.3 Air Traffic Control & Airline Capability and Impact Analyses

The results section that achieves the second sub-objective (4.2) consists of two subsections: the impact on and capabilities of air traffic control, and the impact on and capabilities of the airlines. The steps taken to perform these analyses are described next.

To assess the effect of the implementation of RNP AR approach procedures at EHAM on the air traffic management of LVNL and LVNL's capability in transitioning to a full RNP AR operation, the following five steps are performed.

1. To evaluate the impact of RNP AR procedures on the wake turbulence separation standards enforced by LVNL for managing inbound and outbound traffic at EHAM, EASA RECAT-EU separation standards for the current IAPs at EHAM are examined and compared to the standards for RNP AR approaches.
2. To analyse the influence of RNP AR procedures on LVNL's TMA management, data is collected on the current TMA management of LVNL, including the absence of FARs and speed control strategies, by assessing LVNL traffic data and conducting qualitative interviews with air traffic controllers.
3. To evaluate the impact of integrating RNP AR procedures on the workload of air traffic controllers at EHAM, qualitative data is gathered from interviews with air traffic controllers regarding RNP AR.
4. To assess the current RNP AR knowledge and experience of air traffic controllers at EHAM, qualitative data is collected on the current experience levels of LVNL air traffic controllers, by examining quantitative historic traffic handling data of these air traffic controllers.
5. To identify gaps in knowledge and skills related to RNP AR procedures and determine the specific training requirements to address these gaps, relevant ICAO regulations on air traffic controller training requirements are used.

As mentioned above, a few short unstructured interviews have been conducted with air traffic controllers and LVNL supervisors to address this research's second sub-objective. The interviews consisted of the questions below. Not all questions have been asked in every interview, only when applicable to the interviewee's work.

The following questions are related to RNP AR approach procedures.

- What is your experience level with RNP and RNP AR approach procedures?
- What positive and negative impact would RNP AR approaches have on the current operation?
- What would be the best training approach for LVNL to prepare air traffic controllers to handle RNP AR traffic?

The following questions are related to handling mixed-equipped traffic.

- What is your experience with handling mixed-equipped (RNP AR and non-RNP capable aircraft) traffic?
- What would be the impact of handling mixed-equipped traffic on the current operation?
- What support tools would be needed/preferred when operating mixed-equipped traffic?

The following questions are related to LVNL's TMA management.

- What would be the impact of implementing RNP AR procedures on the current approach strategy of LVNL? To which degree would vectoring still be needed or possible?
- What will become the new approach strategy of LVNL? Only speed control?
- Which strategy would you prefer in the future, when handling RNP AR and EoR traffic only?

The following questions are related to EoR operations.

- What is your experience with independent parallel or EoR operations?
- What impact would EoR operations have on the current operation?
- What will be the impact of EoR operations on the runway offset/separation at EHAM?

To assess the capability of airlines operating at EHAM in transitioning to a full RNP AR operation and the effect of the implementation of RNP AR approach procedures on airline operations, the following six steps are taken.

1. To comprehensively understand current airline operations at EHAM, quantitative data on the number of air transport movements by top airlines (KLM, EasyJet, Transavia, Delta Air Lines) and the aircraft usage per type is studied using EHAM annual traffic reports.
2. To determine the RNP AR capabilities of aircraft operating at EHAM, considering the necessary RNP AR requirements established by ICAO, PBN fleet capability data from the EUROCONTROL CNS dashboard for aircraft operating at EHAM from 2017 to 2024 is analysed.
3. To determine the fleet capabilities of major airlines at EHAM regarding their readiness for RNP AR operations, data is analysed on current and future fleet plans and upgrade strategies, which is provided by KLM through collaboration with the KDC and the other biggest airlines at EHAM.
4. To evaluate the training requirements and current readiness of flight crews for conducting RNP AR procedures, current training programs and certification statuses of the flight crews at the major airlines is assessed. Current flight crew RNP AR statuses were provided by KLM.
5. To evaluate the current experience and knowledge of those flight crews, quantitative data on the knowledge and experience levels is analysed, which was provided by KLM.
6. To evaluate the operational benefits and considerations for airlines at EHAM in transitioning to RNP AR procedures, focusing on track miles, fuel consumption, and environmental factors, the initial RNP AR trials of KLM in 2023 for runway 18R at EHAM are used.

3.4 Approach Simulations Benefit Analysis

The results section that achieves the third sub-objective (4.3), consists of two subsections: the performance results and the environmental results. The steps taken to perform these assessments are described next.

To define the exact performance and environmental differences between the relevant IAPs at EHAM, the following four steps are performed.

1. To analyse and compare the track miles of RNAV, RNP, and RNP AR approach procedures for runway 18R at EHAM (the most used runway and the same runway used in the KLM RNP AR trials) by simulation, specific waypoints and their associated height and speed restrictions are chosen as input data. Simulation techniques at Innovation Labs (iLabs) are used to simulate these approaches. iLabs is an innovation hub at LVNL, aimed at innovating air traffic control systems and procedures.
2. The input data (waypoints and restrictions) for the iLabs simulation of the RNAV approach simulation is based on the current RNAV night transition for runway 18R at EHAM and the input data (waypoints and restrictions) for the iLabs simulation of the RNP approach simulation is based on the current RNP night transition for runway 18R at EHAM. The input data (waypoints and restrictions) for the iLabs simulation of the RNP AR approach simulation is based on the flight track of the 2023 KLM RNP AR trials for runway 18R at EHAM, which crosses the North Sea Canal.
3. To evaluate and compare the environmental impact of RNAV, RNP, and RNP AR approach procedures for runway 18R at EHAM by simulation, an appropriate emission measurement system is used.
4. For CO_2 emissions, the ICAO Carbon Emissions Calculator Methodology is used. This methodology states that the fuel burn (based on the flight tracks) is converted to CO2 emissions by multiplying it by a factor of 3.16. This is shown in Formula 1 below. The aircraft fuel burn is indicated as 'eq' and the load factor of the aircraft as 'n'. The load factor indicates the percentage of available seating capacity that has been filled with passengers.

$$CO_2\ emissions\ (kg) = 3.16 * eq * n \tag{1}$$

3.5 Concept of Operations & Roadmap

The results section that achieves the fourth sub-objective (4.3), consists of two subsections: the implementation & achievability of the end goal and the RNP AR roadmap for EHAM. The following steps outline how these sections are investigated.

To determine the most suitable RNP AR implementation process approach for the stakeholders involved, the following five steps are performed.

1. To evaluate which RNP AR enablers are required to be implemented before the start of the RNP AR roadmap, ICAO guidelines on RNP AR implementation requirements and LVNL's current TMA management are analysed.
2. Data from LVNL regarding the existing airspace structure around FARs, CDOs and separation-independent operations at EHAM is examined to determine what steps need to be taken to implement the first RNP AR approach procedure.
3. To assess the achievability of the end goal, transitioning to a full RNP AR operation, results and conclusions from prior paragraphs are combined, including the airspace, airport, ATC and airline analyses.
4. The starting point of the RNP AR roadmap for EHAM is defined based on the runway characteristics analysed in 4.1.2.
5. The development of the roadmap results from findings in the airport, airspace, capacity, ATC and airline analyses. The timeline of the roadmap is based on assumed implementation and evaluation periods between the different implementation steps.

4. Results

This chapter contains all of the results of this thesis. The chapter encompasses the following: the airspace and airport analyses, which are the foundation for the airspace capacity analysis (4.1), the air traffic control and airlines RNP AR capability and impact analyses (4.2), the approach simulations for runway 18R (4.3), and the concept of operations, including the RNP AR roadmap for EHAM (4.4). Each sub-chapter is completed with a table which includes all important takeaways.

4.1 Airspace, Airport & Capacity Analyses

This sub-chapter will answer the first research question, thus presenting the impact of the implementation of RNP AR approach procedures on the current airspace capacity at EHAM by analysing the airspace, airport and capacity characteristics of EHAM.

4.1.1 Airspace Analysis

The following section will elaborate on the main airspace characteristics of EHAM and on the capability of the airspace around EHAM to handle mixed RNP AR capable and non-RNP AR capable air traffic.

4.1.1.1 Airspace Characteristics

EHAM is situated in the middle of the Amsterdam FIR (Flight Information Region), which is controlled by Air Traffic Control the Netherlands (LVNL). Flight patterns within the Amsterdam FIR are primarily determined by the origins of air traffic destined for EHAM. Arriving traffic at EHAM follows three distinct traffic flows: ARTIP, RIVER, and SUGOL, each serving as Initial Approach Fixes (IAFs). Each IAF directs arriving flights through EHAA to their assigned runways at EHAM. Figure 4.1.1 shows the Amsterdam FIR, EHAA.

Figure 4.1.1: The Amsterdam FIR, EHAA (Schiphol, 2023)

4.1.1.2 Instrument Approaches

EHAM provides a wide range of instrument approach procedures (IAPs) designed to adapt to various aircraft capabilities and diverse weather conditions. The available IAPs include ILS (Instrument Landing System), LOC (Localizer) and RNP (Required Navigation Performance) approaches. Currently, there are no RNP AR (Required Navigation Performance Authorization Required) approach procedures available at the airport (LVNL, 2024).

Optimizing descent procedures in accordance with instrument approach procedures presents a challenge within the operation at EHAM, because of capacity limits and weather conditions. This challenge may be mitigated through the implementation of RNP AR. At present, EHAM's Terminal Manoeuvring Area (TMA) has no defined fixed arrival routes during daytime and instrument approach procedures initiate from intermediate fixes only after aircraft have established alignment on final approach tracks. For now, vectoring is favoured at EHAM due to its capacity advantages, sustaining the current landing rate of 36-38 landings per hour per runway. During night-time operations at EHAM, LVNL uses transition approaches (such as RNAV to RNP and RNAV to ILS) to connect IAFs via predetermined routes. Over portions of these transitions crossing the North Sea, LVNL is authorized to deviate from established routes to facilitate noise and fuel optimization of landing sequences (LVNL, 2024).

4.1.1.3 Mixed Traffic Separation

When implementing RNP AR, it is crucial to understand the necessary separation buffers arising from a combination of RNP AR and non-RNP AR traffic, which would be the case at EHAM. The following separation criteria are relevant for this research on the implementation of RNP AR: Lateral separation of arriving aircraft using IAPs will exist where the distance between any combination of RNAV 1 with RNAV 1, or RNP or RNP AR approaches is less than 7 NM, where the distance between any combination of RNP with RNP AR approaches is less than 5 NM, or where the protected areas of paths designed using obstacle clearance standards do not overlap (ICAO, 2016).

The main difference between the lateral separation of RNP and RNP AR is the definition of the protection areas (semi-widths) (EUROCONTROL, n.d.). For RNP AR procedures, the semi-width is defined as 2 x RNP navigation accuracy requirement, which can be as low as 0.1 NM, but 0.3 NM is assumed. For RNP procedures, the semi-width is defined as 2,5 x RNP, which can be as low as 0.3 NM, but 1 NM is assumed. These differences in NM can be explained by looking at the lateral navigation accuracies of RNP and RNP AR per flight phase in Table 4.1.1

Table 4.1.1: Navigation specifications and their lateral navigation accuracy per flight phase in NM (EUROCONTROL, 2020)

	En route		Arrival	Approach				Departure
	Oceanic	Continental	ARR	Initial	Intermediate	Final	Missed	DEP
RNAV 1	-	1	1	1	1	-	1	1
RNP	-	-	-	1	1	0.3	1	-
RNP AR	-	-	-	1 – 0.1	1 – 0.1	0.3 – 0.1	1 – 0.1	-

Additionally, RNP AR has no secondary buffer zones of 0,5 RNP, unlike RNP approaches (EUROCONTROL, n.d.). This explains the different semi-widths between RNP and RNP AR, which are shown in Figure 4.1.2. Taking the two above-mentioned considerations into account and adhering to the requirement that two instrument procedures remain laterally separated as long as their protection areas do not overlap, it can be concluded that RNP AR and RNP approaches could operate in closer proximity compared to two RNP approaches. The impact of a mixed-equipment approach operation on the air traffic controller will be further elaborated in 4.2.1

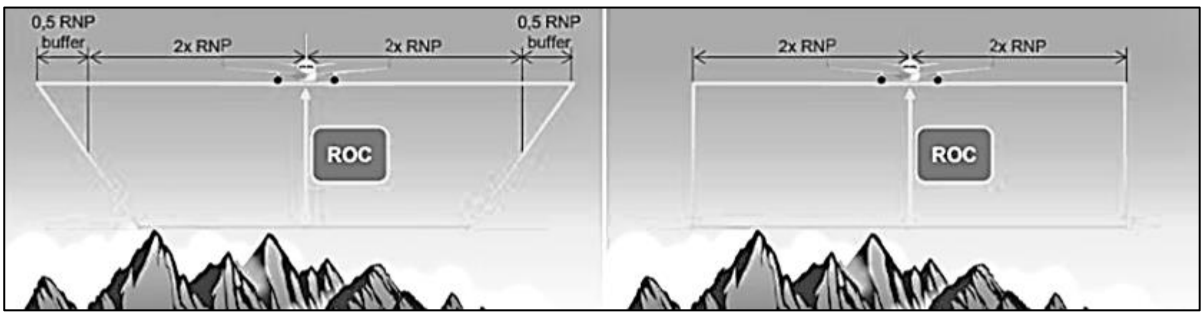

Figure 4.1.2: Lateral protection areas of RNP (left) and RNP AR (right) (NAVBLUE, 2021)

4.1.2 Airport Analysis

The following section will explain the runway characteristics of EHAM and its single, dual and independent parallel runway usage.

4.1.2.1 Runway Characteristics

EHAM has a runway system that includes six runways in multiple wind directions. The runway system consists of single, parallel and intersecting runways. This variety of runways allows EHAM to facilitate arrivals and departures in various conditions. LVNL, which manages take-off and landing authorization, anticipates achieving a peak hour handling capacity of up to 36 landings per hour per runway during inbound peak periods (LVNL, 2024). An overview of the runway layout of EHAM is shown in Figure 4.1.3.

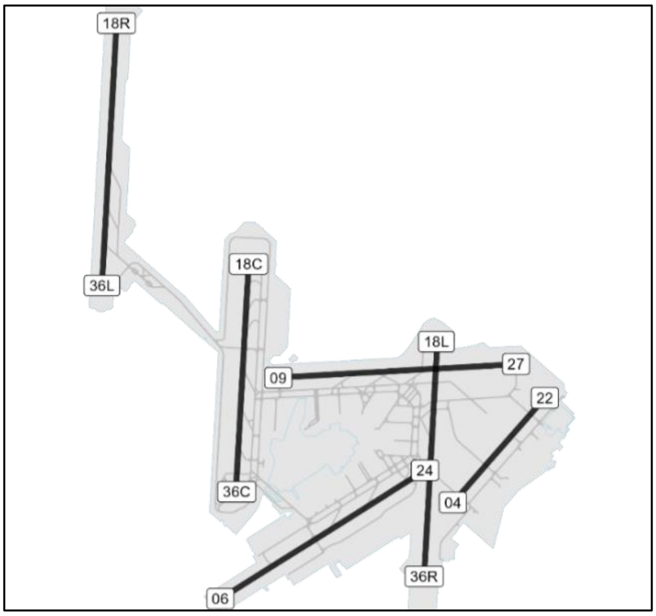

Figure 4.1.3: Amsterdam Airport Schiphol runway layout (EUROCONTROL, 2019)

Runway availability at EHAM is decided by spatial and environmental circumstances at and around the airport which restrict runway usage at certain periods under certain conditions. The runway availability at EHAM is shown in Table 4.1.2. It can be seen that not all runways are available at all times. During night-time (21:30-05:30), most runways are limited in availability (Schiphol, 2023). Furthermore, outside peak periods and during night-time, one departure runway and one landing runway will typically be designated. In outbound peak hours, two departure runways and one landing runway may be utilized, while during inbound peak hours, one departure runway and two landing runways may be operational (Schiphol, 2023).

Table 4.1.2: EHAM runway night-time availability for arrivals and departures (Schiphol, 2023)

Unavailable Runway	Night-time Arrivals	Night-time Departures
04 + 22	✗	✗
09 + 27	✗	✗
18L	✗	✗
18C	✗	✓
18R	✓	✗
24	✗	✓
36L	✗	✓
36C	✓	✗
36R	✗	✓

As was mentioned in 4.1.1, EHAM offers a comprehensive selection of IAPs tailored to accommodate diverse aircraft capabilities and fluctuating weather conditions. These procedures include ILS, LOC, and RNP approaches (FlightAware, 2024). To understand the instrument approach procedure availability per runway, an overview is shown in Table 4.1.3. Currently, RNP approaches are allowed on every runway at the airport, while some runways do not allow ILS or LOC approaches. RNP AR approach procedures are not yet available at EHAM.

Table 4.1.3: EHAM available instrument approach procedures per runway (FlightAware, 2024)

	04	06	09	18C	18R	22	24	27	36C	36R
RNAV	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
LOC	✗	✓	✗	✓	✓	✓	✗	✓	✓	✓
ILS	✗	✓	✗	✓	✓	✓	✗	✓	✓	✓
RNP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RNP AR	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

EHAM has had a relevantly constant runway utilization and runway traffic distribution over the last few years. The predominant landing runways at EHAM include runways 06, 18R, 36R, 18C, 36C, and 27, with runways 04, 09, 22, and 24 only used under limited conditions (European Commission, 2018). Over the period spanning 2018 to 2023, runway 18R was utilized 49% of the time, runway 06 32% of the time, and runway 18C 14% of the time.

4.1.2.2 Parallel Runways

To completely utilize the independent parallel approach advantages of RNP AR, it is crucial to understand how the runways at EHAM are used. Not only according to which procedures, but also if a runway is used for single, dual, independent or converging arrival operations. The most used runways for only single usage are runways 18R, 06, and 27 (LVNL, 2023). For dual runway operations at EHAM, an overview can be found in Table 4.1.4. It can be seen that EHAM currently has two parallel runway combinations, 18R & 18C and 36R & 36C. Combination 18R & 18C has the most usage (8.6%) of all available combinations (LVNL, 2023). So, it can be concluded that LVNL prefers parallel runways for approach operations, instead of converging runways.

Table 4.1.4: Distribution of dual runway usage at EHAM (LVNL, 2023)

Parallel Runways	Converging Runways	Combination Usage
18R & 18C		8.6 %
36R & 36C		1.3 %
	18R & 22	1.1 %
	06 & 18R	0.6 %
	18C & 22	0.2 %
	18R & 24	0.1 %
	06 & 36R	5.7 %
	27 & 18R	2.4 %
	27 & 36C	0.9 %

4.1.3 Airspace Capacity

The following section will assess the differences in airspace capacity at EHAM when implementing RNP AR, by examining approach features, runway separations, design concerns and visibility conditions.

4.1.3.1 Approach Capacity

To understand the airspace capacity of EHAM regarding operating according to RNP AR in the future. One needs to take a look at the current RNP approaches used and their corresponding minima and clearance values. Currently, the following RNP approaches are used at EHAM: LNAV, LNAV/VNAV and LPV. LNAV is a 2D non-precision RNP approach providing only lateral guidance, LNAV/VNAV is a 3D RNP approach providing both lateral and barometric vertical guidance (Baro-VNAV), and LPV is a 3D RNP approach providing geometric vertical guidance based on SBAS (Satellite-based Augmentation System) (ICAO, 2021).

Depending on the type of RNP approach being flown, these approaches can feature up to three different minimum lines. These minima are expressed in Decision Height (DH). For LNAV approaches, the DH minimum is 250 ft. For LNAV/VNAV approaches, the Baro-VNAV DH minimum is 250 ft. For LPV approaches, the DH minimum is 200 ft (ICAO, 2021). Approach minima remain consistent for both single and parallel operations, provided that the final approach and possible missed approach segments remain unchanged. Table 4.1.5 shows an overview of the expected lowest DH for all used RNP approaches at EHAM.

Table 4.1.5: RPN approaches at EHAM with their guidance and decision height (ICAO, 2021)

RNP Approach	Guidance	Decision Height
LNAV	2D Non Precision	250 ft
LNAV / VNAV	3D Baro-VNAV	250 ft
LPV	3D SBAS	200 ft

To understand the impact of these different approach minima on the capacity at EHAM, the effect on the obstacle clearance heights (OCH) per aircraft category needs to be assessed. Runway 18R, the busiest runway at the airport, is used as a reference, as can be seen in Table 4.1.6. The DH limitation of ILS approaches is 200 ft (ICAO, 2016), which is reflected in low OCH values in Table 4.1.6. When comparing the ILS approach OCH values to the values of the best RNP approach, LPV, it can be concluded that ILS is still the IAP with the lowest clearance values to ensure accessibility of the airport during periods with low visibility, as its impact on maintaining maximum capacity at EHAM is the highest.

Table 4.1.6: Obstacle clearance heights (OCH) of all available instrument approach procedures for runway 18R at EHAM (eAIP, 2023)

Aircraft Category	ILS	RNP (LPV)	RNP AR
A	141 ft	213 ft	✕
B	151 ft	225 ft	✕
C	164 ft	233 ft	✕
D	178 ft	244 ft	✕

RNP AR approaches utilize Baro-VNAV, like LNAV/VNAV approaches (ICAO, 2023). Therefore, the DH minimum of RNP AR approaches is also 250 ft, which would make RNP AR approaches worse than ILS approaches. However, lower RNP values may sometimes be established for an RNP AR approach. But, adherence to these values is allowed solely when a significant operational advantage can be achieved, and after a thorough analysis of aircraft eligibility requirements. A thorough analysis of the airline’s fleet capabilities will be examined in 4.2.2.

Upon analysing the various minima options available for approaches to runway 18R at EHAM, along with their respective impacts and consequences, it becomes evident that ILS approaches are better in terms of DH minima. However, mixed procedures are a promising alternative. These procedures involve extended fixed arrival routes while maintaining ILS-based final approach segments, thereby ensuring low approach minima. Looking ahead, the integration of RNP AR with ILS procedures could provide enhanced lateral and vertical path accuracy in the final approach segment. The combination of RNP AR and ILS approaches has the potential to mitigate challenges associated with approach minima while offering noise and environmental benefits across all weather conditions.

4.1.3.2 Runway Separation

Another important aspect to consider when examining the impact of RNP AR procedures on the capacity of EHAM is runway offset. Especially the runway offset of parallel runways, because RNP AR allows for independent parallel Established on RNP AR (EoR) approaches. Runway offset serves as a buffer for separation, incorporated into the design of instrument approach procedures like RNP AR. This buffer provides longitudinal separation, particularly useful when implementing identical procedures for multiple parallel runways. As discussed in 4.1.2.2, EHAM currently operates two sets of parallel runways, 36C + 36R and 18C + 18R. The runway offset at EHAM is 1.67 NM for 36C + 36R and 1.89 NM for 18C + 18R (LVNL, 2023). Figure 4.1.4 illustrates these runway separations. Designing RNP AR procedures for these parallel runways could allow for slightly reduced buffers, thus increasing the capacity at the airport slightly.

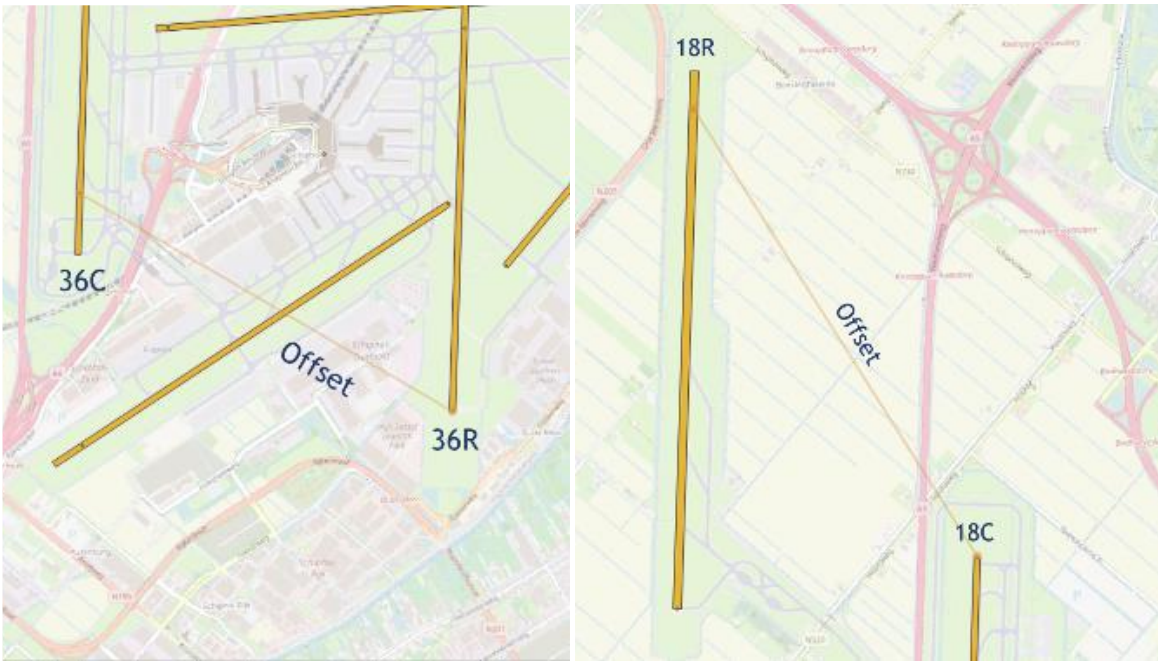

Figure 4.1.4: The runway separation of runways 18C & 18R, and runways 36C & 36R at EHAM (LVNL, 2023)

However, air traffic controllers at LVNL prefer that the runway offset not be reduced when designing parallel RNP AR procedures (LVNL, 2024). This would ensure symmetrical approaches when operating RNP and RNP AR mixed equipment approaches simultaneously. This way the workload of the air traffic controller would not be increased, because the two different traffic flows would turn and be aligned with the runway centre line at the same points. Figure 4.1.5 shows an example of the ideal symmetrical (left) and the unideal non-symmetrical (right) approach procedures at runways 18C + 18R at EHAM. More on the impact of RNP AR on the air traffic controller in 4.2.1.

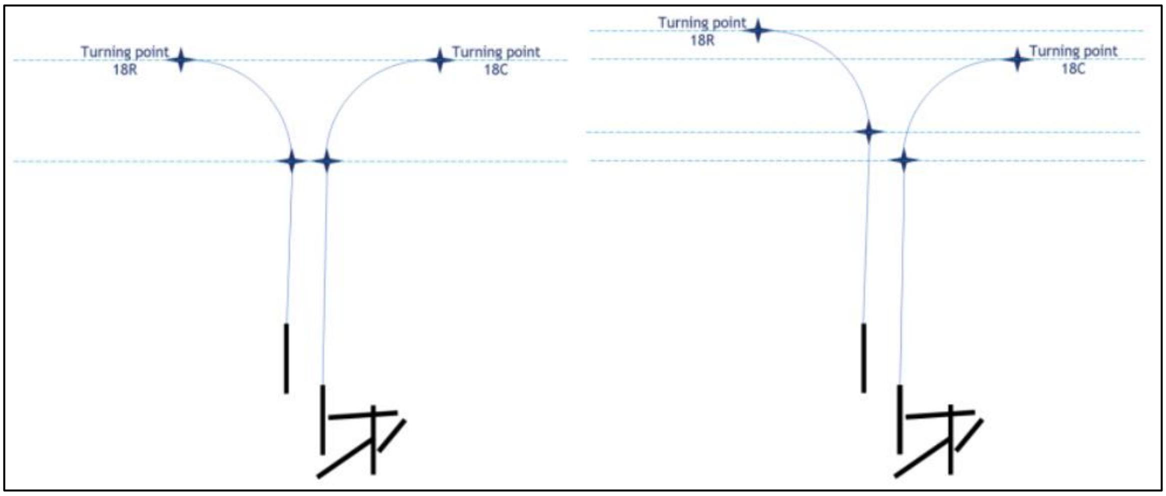

Figure 4.1.5: Symmetrical approach procedures (left) and non-symmetrical approach procedure (right) at runways 18R & 18C at EHAM (LVNL, 2023)

4.1.3.3 Design Concerns

The implementation of RNP AR comes with strict concerns and constraints. The following design considerations need to be taken into account when designing approaches for the RNP AR procedures, and the impact of these approach designs on the capacity of the airport.

One of the main requirements of night-time operations at EHAM is the prohibition of parallel approach operations (Schiphol, 2023). Consequently, employing RNP AR procedures to operate according to EoR is not possible during night-time hours, given these operational constraints. Single RNP AR approach procedures could be implemented at EHAM separately from the daytime RNP AR approach procedures. In the event that the design of an RNP AR approach procedure varies between day and night operations, collaboration between ATC and flight procedure designers during the design stages is essential to ensure clear differentiation between the procedures for flight crew and ATC.

Another RNP AR design and communication consideration is regarding an approach that would connect to two runways. Without any communications with the flight crew or additional system support, ATC cannot determine which runway the aircraft is being directed to, until the aircraft has exited the common part of the flight path. Figure 4.1.6 illustrates an example where, prior to reaching the end of the common flight path, it remains unclear to ATC whether the aircraft is following the transition to the left or right runway. This uncertainty can be addressed by ensuring that ATC has already instructed the aircraft for one of the two transitions (LVNL, 2023).

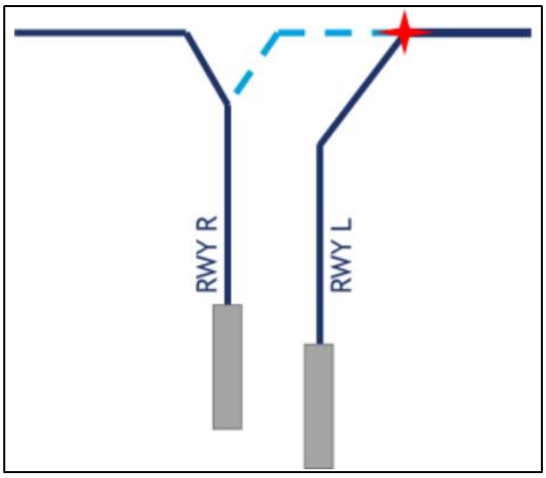

Figure 4.1.6: Joint RNP AR approach transition to two different parallel runways (LVNL, 2023)

4.1.3.4 Visibility Conditions

One of the operational concerns at EHAM which has a high influence on the airport's capacity is the local visibility conditions, which can be relatively precarious in the Netherlands throughout the year. In the event of low visibility occurrences at EHAM, the total capacity of ATC decreases. To guarantee both aircraft safety and the most effective utilization of ATC resources, EHAM has established low visibility procedures in accordance with relevant ICAO regulations (eAIP, 2023). These procedures are organized into four phases, referred to as BZOs (Limited Visibility Conditions). The specifications of each phase depend upon the runway visual range (RVR) and the cloud ceiling conditions at EHAM (Schiphol, 2022). An overview of the BZO phases with their corresponding conditions, impact and ILS category can be seen in Table 4.1.7.

Table 4.1.7: BZO conditions at EHAM with their corresponding conditions, impact and ILS category (Schiphol, 2022)

BZO Phase	Conditions	Impact	ILS Category
A	RVR ≤ 1500 m & ceiling ≤ 300 ft	Reduced ground operations	Cat I
B	RVR < 500 m & ceiling < 200 ft	Runway use restricted	Cat II
C	RVR < 350 m	Runway use restricted	Cat III
D	RVR < 200 m	One ARR runway + One DEP runway	Cat III

RNP AR approach procedures have not been implemented at EHAM, so they are not integrated into the low visibility condition protocols. However, as RNP AR approach procedures currently do not offer superior capabilities compared to an ILS approach Cat I, it is assumed that they could be employed under visibility conditions categorized as BZO-A. When examining the effect of the implementation of RNP AR at EHAM on the capacity of the airport for all meteorological conditions, it is important to look at the weather distribution throughout the year and how often certain category BZO-A occurs.

Table 4.1.8: Visibility conditions at EHAM during the operational period 2016 -2023 (LVNL, 2023)

Operational Period	BZO - A	BZO - B	BZO - C	BZO - D
2016 - 2023	98.7 %	1.0 %	0.2 %	0.1 %

Table 4.1.8 shows an overview of the distribution of visibility conditions at EHAM between 2016 and 2023. The results of Table 4.1.8 show that the conditions for the category BZO-A occur 98.7% of the time. So, both RNP AR and ILS Cat I approach procedures are available at EHAM 98.7% of the time (LVNL, 2023). Based on these findings it can be concluded that using RNP AR as the primary approach for the main landing runways at EHAM in the future will have the least amount of negative effect on the airport capacity, compared to other instrument approach procedures.

Key Takeaways of Sub-Chapter 4.1

Section	Main Takeaways
Airspace Analysis	EHAM IAFs: RIVER + SUGOL + ARTIP RNAV, RNP and RNP AR: Different semi-withs & protection areas
Airport Analysis	6 runways: RNP available, no RNP AR Parallel combination 18R & 18C most used
Approach Capacity	Current minima: ILS > RNP AR, Future: combine RNP AR with ILS
Runway Separation	RNP AR: No separation reduction But, allows symmetrical parallel operations
Design Concerns	Procedure designer + ATC + flight crew communication = crucial
Visibility Conditions	ILS & RNP AR available 98.7%, no RNP AR influence

4.2 Air Traffic Control & Airline Capabilities

This sub-chapter will answer the second research question, thus elaborating on the capabilities of LVNL and the airlines operating at EHAM of transitioning to a full RNP AR operation and assessing the impact of this transition on the operation of these stakeholders.

4.2.1 Air Traffic Control Capability

The following section will elaborate on the impact of implementing RNP AR and the capability of LVNL to handle RNP AR traffic at EHAM, by examining separation standards, LVNL's TMA management and the perspective of the air traffic controller.

4.2.1.1 Separation Standards

Air Traffic Control the Netherlands (LVNL) is responsible for handling all inbound and outbound traffic at EHAM. Many factors influence the capabilities and operational capacity of LVNL at EHAM. One of these factors is turbulence separation during the approach. Upon arrival at EHAM, wake turbulence separation within the Terminal Manoeuvring Area (TMA) and Control Zone (CTR) follows the EASA RECAT-EU regulations (EASA, 2017). Table 4.2.1 shows an overview of the EASA RECAT-EU separation standards for approaching aircraft. The values in the table count for all instrument approach procedures currently flown at EHAM.

Table 4.2.1: RECAT-EU separation minima for arriving aircraft at EHAM (EASA, 2017)

Leading (left) / Following (right) Aircraft	A	B	C	D	E	F
A	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
B	-	3 NM	4 NM	4 NM	5 NM	7 NM
C	-	-	3 NM	3 NM	4 NM	6 NM
D	-	-	-	-	-	5 NM
E	-	-	-	-	-	4 NM
F	-	-	-	-	-	3 NM

The same RECAT-EU wake turbulence separation standards as in Table 4.2.1 also apply for aircraft approaching according to RNP AR procedures (ICAO, 2023). So, the separation criteria outlined in Table 4.2.1 for sequencing incoming traffic at EHAM remain valid. As a result, implementing RNP AR does not directly enhance or reduce LVNL's approach capacity concerning wake turbulence separation standards.

4.2.1.2 TMA Management

The introduction of RNP AR approaches decreases aircraft mileage within the TMA, particularly in dual landing runway scenarios (ICAO, 2023). However, this change may result in controllers losing some control, as aircraft will primarily follow fixed arrival routes (FARs), shifting the focus towards speed control as the primary strategy (LVNL, 2024). This transition could potentially lead to capacity reductions if aircraft are insufficiently spaced or spaced too wide at the start of their routes. Therefore, the presence of system support to assist air traffic controllers in merging aircraft will be crucial for maintaining maximum capacity levels. Additionally, as control space decreases within the TMA due to the introduction of FARs, a portion of the separation responsibility will shift to the area controllers. This could result in the need for new agreements regarding aircraft delivery to the TMA (LVNL, 2024).

4.2.1.3 Air Traffic Controller

The following two sections are partially based on qualitative interviews with air traffic controllers of LVNL (LVNL, 2024). The questions asked in the short interviews with the air traffic controllers and air navigation specialists can be found in the methodology (3.3).

When considering the integration of RNP AR procedures alongside other instrument approach procedures, various options can be explored. It's important to highlight that these options are likely to significantly influence traffic flows within the EHAM TMA, so their feasibility and impact on air traffic controllers should be thoroughly evaluated.

Firstly, implementing a "best equipped - first served" approach could serve as an encouragement for equipping aircraft and training flight crew for RNP AR. Secondly, prioritizing the implementation of RNP AR for runways that offer the highest capacity and environmental benefits. Thirdly, starting parallel RNP AR operations (including EoR) on runways 36C/36R, as it has the greatest runway separation, allowing for shorter EoR design to ensure safe separation. Lastly, initiating RNP AR operations (including EoR) at runways 18R/18C, given its higher usage compared to the other parallel combination. The most suitable implementation option will be presented in the concept of operations (4.4).

4.2.1.4 Experience & Knowledge

At present, EHAM does not have RNP AR approach procedures, leading to limited air traffic controller experience with these approaches. RNP AR procedures adhere strictly to predetermined paths, restricting air traffic controllers from deviating, which limits flexibility. However, air traffic controllers recognize the preference of flight crew for a consistent approach path and distance to the threshold (LVNL, 2024). In the future, approaches that involve fewer speed restrictions and altitude constraints are preferred by LVNL, diverging from the vectoring method presently employed by LVNL at EHAM. Transitioning from the current approach to implementing RNP AR procedures could be accelerated by designing routes that closely align with existing vector patterns, potentially increasing the acceptance of the air traffic controllers (LVNL, 2024).

When considering the knowledge and skills necessary for air traffic controllers to facilitate RNP AR approach procedures, it's vital to delve into the required training, encompassing both theoretical comprehension and practical application. While the adoption of new approach procedures is not anticipated to present major obstacles, it is important to develop and coordinate training to mitigate potential confidence issues among air traffic controllers and avoid misunderstandings related to these new procedures. A current challenge for air traffic controllers is about effectively handling a fleet with mixed equipment capabilities, encompassing both RNP AR and non-RNP AR capable aircraft (LVNL, 2024). To potentially tackle this challenge in the future, LVNL could implement merge support systems, aiming to streamline approach procedures. Such support systems for managing mixed equipment scenarios might involve the development of precise planning tools for sequencing arrivals over specific points. Additionally, incorporating map overlays with distance markers for merging support and a compliance symbol on aircraft labels to indicate the type of approach being executed would provide further value (LVNL, 2024).

Finally, the personal preference of air traffic controllers for the vectoring strategy is a significant aspect of the current air traffic controller training at LVNL (LVNL, 2024). However, even if RNP AR procedures are introduced at EHAM in the future, not all runways would initially have RNP AR approaches available. So, vectoring would remain a necessary alternative for runways without RNP AR approaches. LVNL air traffic controllers have indicated a preference for a combination of vectoring and speed control for aircraft sequencing (LVNL, 2024). However, with an expected rise in the use of RNP AR approaches, air traffic controllers foresee a decrease in vectoring usage, making speed control the primary method for sequencing aircraft. In an ideal situation, speed control would not be required if all aircraft following RNP AR approaches maintained standard speeds and fell within the same EASA RECAT-EU category (4.2.1.1). Nevertheless, realizing this ideal scenario in the near future is challenging in practice.

4.2.2 Airline Capability

The following sub-chapter elaborates on the impact of implementing RNP AR and the capability of airlines operating at EHAM to transition to a full RNP AR operation, by examining fleet and flight crew requirements and capabilities. The focus will mainly be on KLM.

4.2.2.1 Airline Operations

The airline operations at EHAM are one of the crucial aspects of a time-efficient and achievable transition to a full RNP AR operation at the airport. Fleet and flight crew capabilities are of great importance to consider, given that low equipage values or crew insufficiencies would cause a complex operation. Furthermore, the goal of operating solely according to RNP AR procedures would not be achieved in the proposed timeframe.

In 2023, there were a total of 97 airlines operating at EHAM. Table 4.2.2 shows the top 5 biggest airlines in terms of air transport movements in 2023, and the airlines' share of the total operation. KLM Royal Dutch Airlines, the flag carrier airline of the Netherlands, was the biggest airline in 2023 with 51.8% of the total air transport movements, followed by easyJet with 8.0% and by Transavia with 6.9%. These three airlines alone represent over two-thirds (66.7%) of all yearly flights at EHAM.

Table 4.2.2: Airline operations in 2023 at EHAM (2024, Schiphol)

#	Airline	Air Transport Movements	% of Total
1	KLM	228.956	51.8 %
2	EasyJet	35.482	8.0 %
3	Transavia	30.567	6.9 %
4	Delta Air Lines	11.259	2.5 %
5	Vueling	10.393	2.3 %

To get a comprehension of the aircraft usage at EHAM, an analysis of the yearly aircraft type distribution has been performed. Table 4.2.3 shows the top 5 most used aircraft types at EHAM in 2023. The Boeing 737-800 was the most used aircraft with 21.8% of the total air transport movements, followed by the E-190 with 15.9%, the A320 with 8.5%, and the E-175 with 8.2%. These four aircraft types alone represent over half (54,4%) of all yearly flights at EHAM.

Table 4.2.3: Aircraft usage distribution in 2023 at EHAM (2024, Schiphol)

#	Aircraft	Air Transport Movements	% of Total
1	B737-800	96.558	21.8 %
2	E-190	70.691	15.9 %
3	A320	37.993	8.5 %
4	E-175	36.263	8.2 %
5	A319	24.206	5.4 %

When delving deeper into airline operations in the following sections, it is crucial to concentrate on the four most utilized aircraft types at EHAM and the four biggest airlines. The present and future fleet renewal plans of these airlines are vital to creating the concept of operations and the RNP AR roadmap.

4.2.2.2 Aircraft Capabilities & Requirements

Understanding aircraft RNP AR capabilities is essential for ensuring a safe and efficient transition to a full RNP AR operation at EHAM. The EUROCONTROL CNS (Communication, Navigation & Surveillance) dashboard evaluates the capabilities of flights and aircraft operating in Europe by examining ICAO PBN information (ICAO, 2012) and linking it to data from the EUROCONTROL fleet aircraft database (EUROCONTROL, n.d.). By using the CNS dashboard, a thorough analysis of the PBN capabilities of aircraft arriving at EHAM between 2017 and 2024 has been performed. Table 4.2.4 shows an overview of the RNP and RNP AR capabilities of aircraft operating at EHAM in this period. The PBN capability data is from every first month of the year.

Table 4.2.4: RNP AR capability of aircraft operating at EHAM between 2017-2024 (EUROCONTROL, n.d.)

Date	RNP Capable	RNP AR Capable
01-2017	66.4 %	10.1 %
01-2018	71.4 %	11.3 %
01-2019	78.9 %	15.5 %
01-2020	85.0 %	15.8 %
01-2021	80.5 %	21.1 %
01-2022	83.9 %	16.7 %
01-2023	85.0 %	19.4 %
01-2024	88.3 %	21.9 %

Table 4.2.4 shows that both capability categories are steadily increasing between 2017-2024. The aircraft RNP capability at EHAM rose from 66.4% to 88.3%, while the aircraft RNP AR capability rose from 10.1% to 21.9%. This increase in RNP AR approach-capable aircraft at EHAM is illustrated in Figure 4.2.1. 2022 was the only year without an increase in capable RNP AR aircraft, which was probably a late result of the negative impact of COVID-19 on the aviation sector.

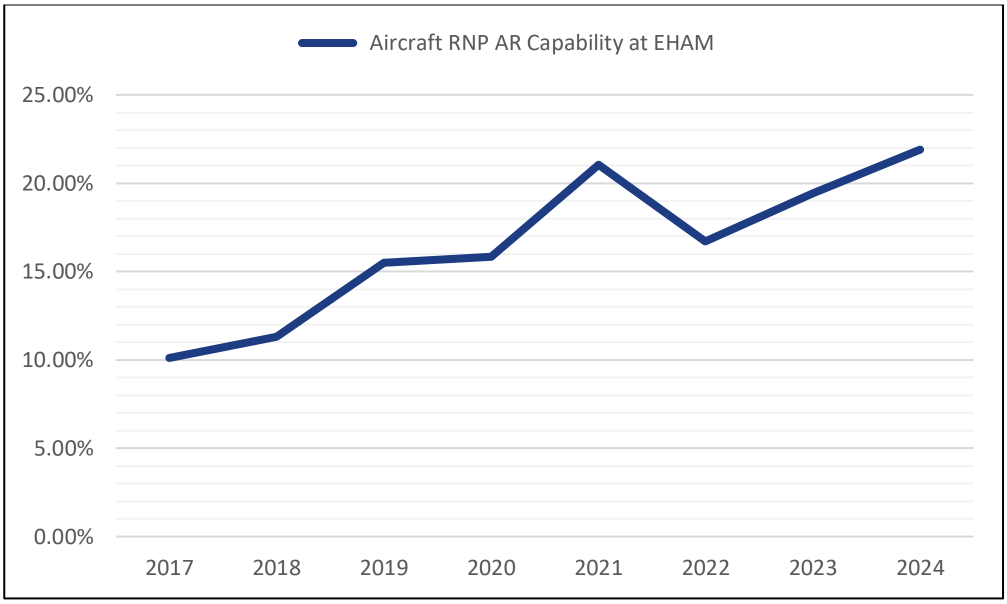

Figure 4.2.1: Percentage of RNP AR capable aircraft at EHAM between 2017 – 2024 (EUROCONTROL, n.d.)

To understand the RNP AR capabilities of the current fleet at EHAM, one has to analyse the RNP AR approach requirements for adequate aircraft. RNP AR approaches require particular aircraft configurations and onboard equipment (ICAO, 2023). The important aircraft requirements for implementing RNP AR and the overall RNP AR status of different aircraft types are outlined below.

Most B737s do not have dual FMS and thus are not certified for RNP AR approaches. But, most B777s, all B787s, and all B73M are RNP AR capable. Furthermore, most Airbus families (A320, A330, A340, A350) have RNP AR certification. The A320/321Neo are also RNP AR certified. Equipping older aircraft in their fleet is costly for airlines because it typically occurs during yearly a C-check, taking up valuable time. Lastly, the design and testing of RNP AR procedures must align with the specific design characteristics and performance capabilities of the respective aircraft (ICAO, 2023).

4.2.2.3 Airline Fleet Capabilities

Considering the overall RNP AR capability at EHAM and the relevant equipment requirements (4.2.2.2), in order to outline an RNP AR roadmap which is representative, the current fleet operating at EHAM needs to be examined. So, this section analyses in more detail the plans of the four biggest airlines operating at EHAM: KLM, EasyJet, Transavia and Delta Air Lines. The KLM Embraer fleet has RNP AR capability, but crew training is still needed. The KLM 777/787 fleet and flight crew are already RNP AR capable and trained. The KLM cargo fleet currently lacks RNP AR capability, but this is a small portion of the fleet that will be replaced by the A350F in the coming years (KLM, 2023). Furthermore, EasyJet's entire fleet is equipped with RNP AR, though they still require the necessary training. Transavia's fleet is fully RNP AR equipped but is in the process of training its flight crew (KLM, 2023). Meanwhile, Delta Air Lines is in the process of equipping their entire fleet by 2025, with their pilots already certified (KLM, 2023).

When looking at the operations of all main airlines at EHAM in Table 4.2.5, in 2023 only around 18% of the fleet operating at EHAM was equipped with RNP AR, with airline projections indicating that this figure will rise to 78% within the next five years (KLM, 2023). Table 4.2.5 shows an overview of the evolution of the RNP AR approach fleet capability of the four biggest airlines at EHAM in the coming years, which was discussed in detail above.

Table 4.2.5: RNP AR equipped fleet of four biggest airlines at EHAM (KLM, 2023)

	2023 % of airline	2025 % of airline	2028 % of airline	2023 % of EHAM	2025 % of EHAM	2028 % of EHAM
KLM	11 %	59 %	100 %	5.7 %	30.8 %	52.2 %
Transavia	100 %	100 %	100 %	7.6 %	7.6 %	7.6 %
EasyJet	-	50 %	100 %	-	4.0 %	8.0 %
Delta Air Lines	100 %	100 %	100 %	2.8 %	2.8 %	2.8 %
Total EHAM				**18 %**	**48 %**	**78 %**

4.2.2.4 Flight Crew

For airlines to be able to operate according to the procedures RNP AR approaches, appropriate flight crew training is essential. These training and certifications for flight crew have strict requirements. Flight crews performing RNP AR approaches are required to follow training that encompasses the following minimum items.

First of all, core training. The flight crew needs to be trained on how RNP systems work. Also, the flight plan requirements and ATC procedures of RNP navigation specifications need to be well-known (ICAO, 2023). For example, mixed equipage environments, separation minima, and changes between different operations. Secondly, training specific to the RNP AR navigation specification is split up into three categories. Relevant air traffic control procedures need to be trained, such as vectoring techniques. Furthermore, the flight crew should be educated on standard RNP AR approach procedures, including adequate approach minima. Lastly, the flight crew should be taught the effects of requesting a route change during an RNP AR approach (ICAO, 2023). Additionally, dedicated training programs may be appropriate for RNP AR approach procedures tailored to specific areas where airlines operate. If RNP AR approaches were to be implemented at EHAM, home-based carriers such as KLM would benefit from incorporating specific airport RNP AR training into its standard training.

4.2.2.5 Experience & Knowledge

The following section will elaborate on the current experience and knowledge of the flight crews of some of the biggest airlines at EHAM: KLM, Transavia and Delta Air Lines.

KLM flight crew has little experience with RNP AR approach procedures. Only 3 destinations out of its network currently require RNP AR approach procedures: Quito, Panama, and San Jose. KLM flight crews are more familiar with flying ILS approaches, as they are often the primary approach procedure available. Transavia flight crews have some experience with RNP AR approach procedures, given that Transavia operates RNP AR approaches at Innsbruck Airport (LOWI), where RNP AR approaches have been available since 2004. Both KLM and Transavia flight crews have not reported any unusual workload when flying an RNP AR approach, indicating that ILS and RNP AR approaches are considered similar in terms of flight crew workload (KLM, 2024). Delta Air Lines flight crews regularly perform RNP AR approach procedures at various airports, especially in the United States. For example, Delta Air Lines is conducting RNP AR operations in Denver, Houston, and Los Angeles (KLM, 2024).

4.2.2.6 Operational Regards

The airspace and airport analyses (4.1.1 & 4.1.2), which resulted in the airspace capacity analysis (4.1.3.), listed the primary benefits of implementing RNP AR approach procedures at EHAM. This section delves into the operational considerations for the airlines at EHAM on the benefits of implementing RNP AR.

First of all, track miles and fuel consumption**.** The specific design characteristics of RNP AR approach procedures, which involve a shorter runway line-up due to the incorporation of an RF leg in the final approach segment (ICAO, 2021), lead to a decrease in track miles during the final approach. For example, KLM conducted initial trials in 2023 utilizing a conceptual RNP AR approach for runway 18R at EHAM (KLM, 2023). An illustration of the approach flight track of these trials is shown in Figure 4.2.2. These trials resulted in an average reduction of 12 NM in track miles per flight compared to existing RIVER approaches for runway 18R (KLM, 2023). This reduction translates to an annual fuel saving of around 100 T, based solely on the RIVER arrivals. Given the current (May 2024) jet fuel price of $278/T in Europe (IATA, 2024), annual fuel savings of 100 T equal to $79.895 (x 0.92 = €73.587) in cost savings for KLM for only a single IAF at EHAM.

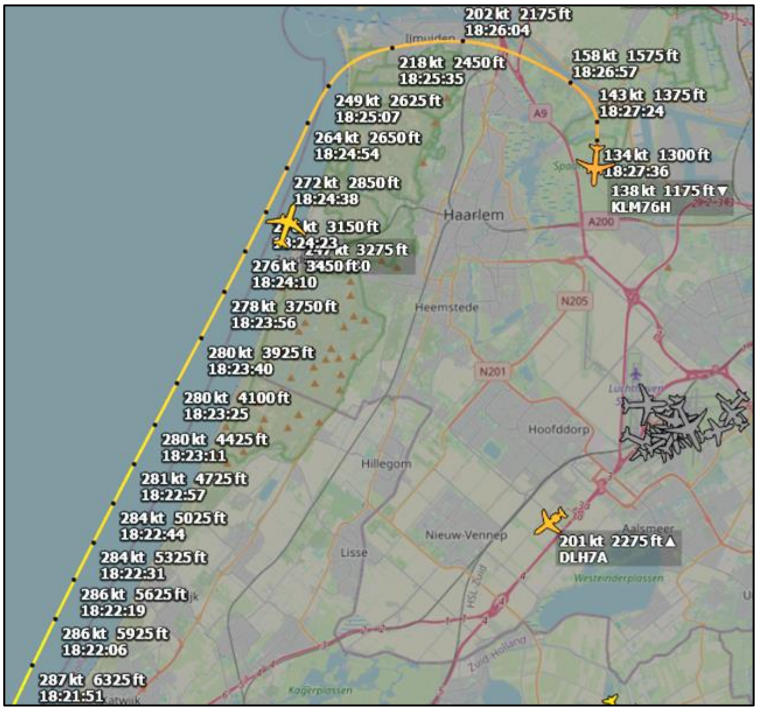

Figure 4.2.2: Approach flight track of the KLM RNP AR trials for runway 18R at EHAM (KLM, 2023)

Secondly, CO_2 emissions. The reduction in track miles and fuel (100 T) translates to 316 T of CO_2 emissions saved per year, using an average calculation of 3.16 kg of CO_2 emissions per 1 kg of fuel (IATA, 2022). This calculation is based solely on KLM flights operating to runway 18R from RIVER. In 2022, the Netherlands emitted 125.4 million T of CO_2 (GCP, 2023). The 316 T of CO_2 emissions saved represent just 0.0003% of the total. While this percentage appears small, if calculated for all airlines operating from RIVER to runway 18R and other runways at EHAM, the reduction in CO_2 emissions becomes more substantial.

Finally, noise reduction. RNP AR approach procedures offer a means to mitigate noise disturbances in residential areas. According to EUROCONTROL, RNP AR approaches can achieve noise level reductions between 1-5 dB(A), compared to non-RNP AR approaches (EUROCONTROL, 2020), from 8-25 NM from the runway threshold. A reduction of 1-2 dB(A) is deemed detectable by the human ear, indicating that the implementation of RNP AR approaches at EHAM is noticeable to neighbouring communities. To get an idea of the significance of a 5 dB(A) noise reduction, Figure 4.2.3 shows the noise contours of EHAM which are colour-spaced by 5 dB(A).

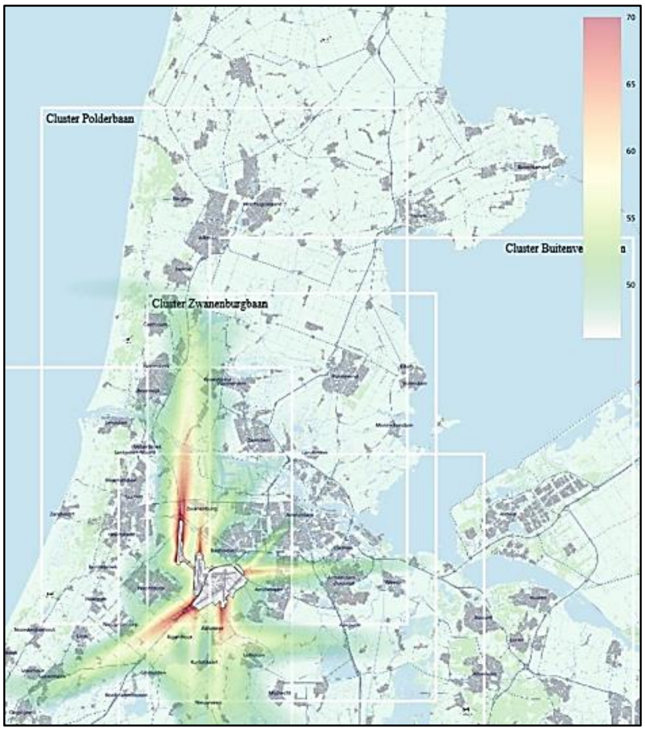

Figure 4.2.3: Distribution of noise pollution during 24 hours at EHAM (Schiphol, 2024)

Key Takeaways of Sub-Chapter 4.2

Section	Main Takeaways
Separation Standards	RNP AR: No positive or negative impact
LVNL's TMA Management	Currently: No FARs → vectoring Future: FARs → RNP AR → speed control only
LVNL Experience & Knowledge	Few experience & knowledge → RNP AR training needed Merging assist tools needed
Aircraft & Fleet RNP AR capability	Aircraft at EHAM: 10.1% (2017)→ 21.9% (now) 4 biggest airline fleets: 18% (now) → 78% (2028)
Flight crew	KLM & Transavia few experience, Delta & EasyJet more All airlines need RNP AR training
Operational Regards	RNP AR airline benefits: Track miles, fuel, CO_2 & noise reductions

4.3 Approach Simulations

This paragraph will answer the third research question, thus assessing the exact performance and environmental differences of the relevant IAPs at EHAM by simulating RNAV, RNP and RNP AR approaches for runway 18R at EHAM.

4.3.1 Approach Performance

The following section will elaborate on the chosen waypoints, including their restrictions, and the track miles results of the RNAV, RNP and RNP AR simulations.

4.3.1.1 Waypoints

To get a better understanding of the exact track mile and environmental differences between certain instrument approach procedures at EHAM, RNAV, RNP and RNP AR approach procedures are simulated for runway 18R at EHAM, using iLabs simulation techniques. The code written to generate the appropriate output can be found in Appendix A. The flight paths of these approach simulations are based on existing LVNL waypoints and assumed height and possible speed restrictions. The following waypoints are used as input for the RNAV approach on runway 18R at EHAM: RIVER, PORWA, AM627, NETOM, NIRSI, AM607, AM608, AM621 (FAF), AM010 (THRE 18R). This input is partially based on the current RNAV to ILS night transition for runway 18R at EHAM. An overview of all waypoints, including their height restriction and speed restriction is shown in Table 4.3.1.

Table 4.3.1: Chosen waypoints and their assumed height and speed restrictions for RNAV approach simulation

Waypoint	Height Restriction	Speed Restriction
RIVER	FL 140	-
PORWA	FL 120	Max 250 kts
AM627	FL 100	Max 250 kts
NETOM	FL 070	Max 250 kts
NIRSI	FL 055	Max 220 kts
AM607	4500 ft	-
AM608	3400 ft	-
AM621	2000 ft	-
AM010	0 ft	-

The following waypoints are used as input for the RNAV approach on runway 18R at EHAM: RIVER, PORWA, AM627, NETOM, NIRSI, AM607, AM133, AM135, AM137, AM621 (FAF), AM010 (THRE 18R). This input is partially based on the current RNP to ILS night transition for runway 18R at EHAM. An overview of all waypoints, including their height restriction and speed restriction is shown in Table 4.3.2.

Table 4.3.2: Chosen waypoints and their assumed height and speed restrictions for RNP approach simulation

Waypoint	Height Restriction	Speed Restriction
RIVER	FL 140	-
PORWA	FL 120	Max 250 kts
AM627	FL 100	Max 250 kts
NETOM	FL 070	Max 250 kts
NIRSI	FL 055	Max 220 kts
AM607	4500 ft	-
AM133	3400 ft	-
AM135	2800 ft	-
AM137	2500 ft	-
AM621	2000 ft	-
AM010	0 ft	-

The following waypoints are used as input for the RNAV approach on runway 18R at EHAM: RIVER, PORWA, AM627, NETOM, AM090, ULPAT, AM094, AM622 (NEW FAF), AM010 (THRE 18R). This input is partially based on the KLM RNP AR trials for runway 18R at EHAM, which were performed in 2023. An overview of all waypoints, including their height restriction and speed restriction is shown in Table 4.3.3. How these waypoints result in different flight paths will be discussed in the next section.

Table 4.3.3: Chosen waypoints and their assumed height and speed restrictions for RNP AR approach simulation

Waypoint	Height Restriction	Speed Restriction
RIVER	FL 140	-
PORWA	FL 110	Max 250 kts
AM627	FL 090	Max 250 kts
NETOM	FL 060	Max 220 kts
AM090	FL 050	Max 200 kts
ULPAT	4000 ft	-
AM094	3000 ft	-
AM622	2000 ft	-
AM010	0 ft	-

4.3.1.2 Track Miles

The iLabs simulations, with the chosen waypoints and corresponding height and speed restrictions as input, result in precise flight paths. The output of the RNAV approach simulation is shown in Table 4.3.4. The RNAV approach output is shown as latitude and longitude coordinates. With these coordinates, the distance between the waypoints and the total distance of this approach procedure from RIVER is calculated. The total distance of the RNAV approach procedure for runway 18R at EHAM is 117.0 km or 63.2 NM.

Table 4.3.4: Track miles results of RNAV approach simulation

Waypoint	Latitude	Longitude	Distance from RIVER (km)
RIVER	51.91276	4.132594	0
PORWA	52.06637	4.116042	17.11803
AM627	52.29338	4.289063	44.98091
NETOM	52.42244	4.387914	60.82427
NIRSI	52.58388	4.513372	80.68238
AM607	52.58388	4.646886	89.70283
AM608	52.53943	4.728142	97.09248
AM621	52.4627	4.721097	105.6369
AM010	52.36026	4.711725	117.0459

The output of the RNP approach simulation is shown in Table 4.3.5. The RNAV approach output is shown as latitude and longitude coordinates. With these coordinates, the distance between the waypoints and the total distance of this approach procedure from RIVER is calculated. The total distance of the RNP approach procedure for runway 18R at EHAM is 116.7 km or 63.0 NM.

Table 4.3.5: Track miles results of RNP approach simulation

Waypoint	Latitude	Longitude	Distance from RIVER (km)
RIVER	51.91276	4.132594	0
PORWA	52.06637	4.116042	17.11803
AM627	52.29338	4.289063	44.98091
NETOM	52.42244	4.387914	60.82427
NIRSI	52.58388	4.513372	80.68238
AM607	52.58388	4.646886	89.70283
AM133	52.54832	4.711898	95.61402
AM135	52.50076	4.728843	101.0256
AM137	52.48643	4.723274	102.6628
AM621	52.4627	4.721097	105.3056
AM010	52.36026	4.711725	116.7147

The difference in NM between the RNAV and the RNP approaches is only around 0.2 NM. This result emphasizes the fact the RNP approaches do not necessarily have big advantages over RNAV approaches when it comes to track miles. But, the strength of RNP approaches is clearly evident when it comes to limiting noise pollution for local residents by adjusting the flight path around neighbourhoods close to the final approach path. For example, the RNP to ILS night transition compared to the RNAV to ILS night transition.

The output of the RNP AR approach simulation is shown in Table 4.3.6. The RNAV approach output is shown as latitude and longitude coordinates. With these coordinates, the distance between the waypoints and the total distance of this approach procedure from RIVER is calculated. The total distance of the RNP AR approach procedure for runway 18R at EHAM is 93.8 km or 50,6 NM.

Table 4.3.6: Track miles results of RNP AR approach simulation

Waypoint	Latitude	Longitude	Distance from RIVER (km)
RIVER	51.91276	4.132594	0
PORWA	52.06637	4.116042	17.11803
AM627	52.29338	4.289063	44.98091
NETOM	52.42244	4.387914	60.82427
AM090	52.46722	4.534364	71.92903
ULPAT	52.47	4.595	76.04808
AM094	52.46608	4.661339	80.56299
AM622	52.42673	4.7178	86.37596
AM010	52.36026	4.711725	93.77851

When comparing the total distance of the RNP AR flight path with the other IAPs, it becomes clear that the distance is significantly reduced. The major advantages of the RNP AR approach compared to RNAV and RNP allow aircraft to line up with the runway much closer to the runway THRE. This can be seen when looking at the flight track of the simulated RNP AR approach for runway 18R at EHAM, which is illustrated in Figure 4.3.1. The RNP AR flight path crossed the North Sea Canal at waypoint ULPAT, which allowed the aircraft to line up with runway 18R at AM622, whereas the other IAPs lined up with the runway at AM621.

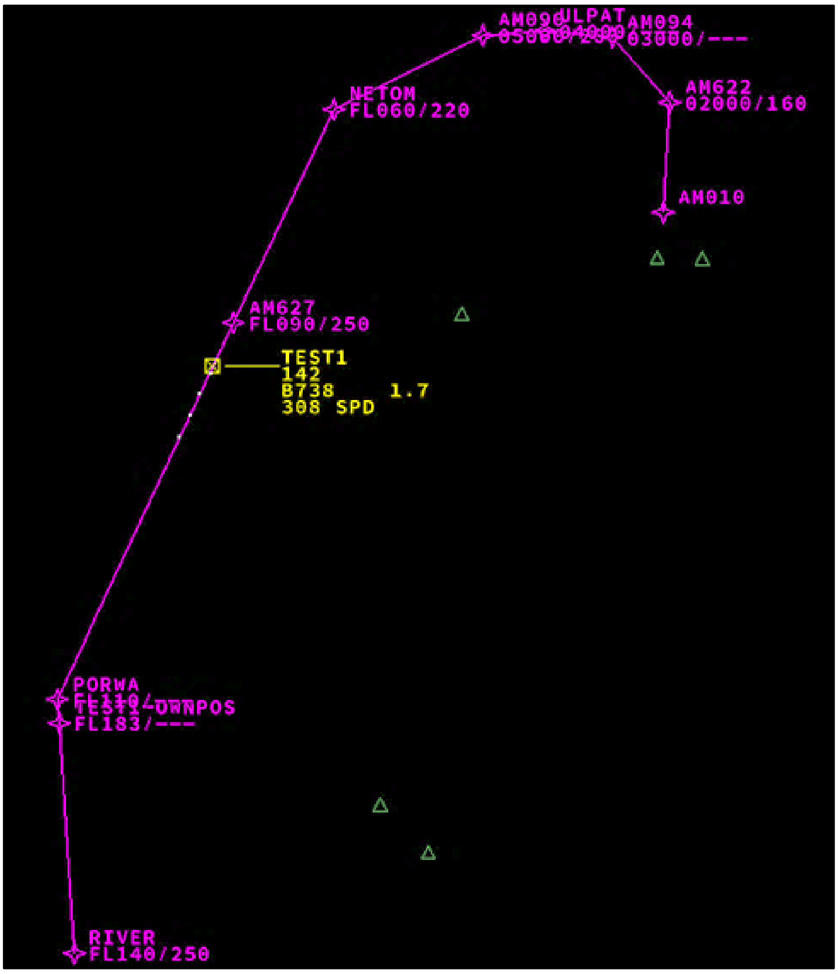

Figure 4.3.1: Flight path of RNP AR approach simulation for runway 18R at EHAM (Post, 2024)

4.3.2 Environmental Impact

The following section will evaluate the environmental impact of the simulated approaches and compare the environmental advantages of RNP AR procedures against the other simulated IAPs.

4.3.2.1 CO_2 Emissions

To get a comprehensive understanding of the environmental impact of the simulated IAPs, it is crucial to look at the amount of CO_2 emissions produced. To be able to calculate the total amount of CO_2 emissions per approach procedure, the track miles and fuel consumption is needed. The previous section elaborated on the track miles, this section will examine the fuel consumption.

For all fuel burn calculations, the B737-800 I used. This aircraft type has the highest usage % at EHAM. The fuel burn rate of the B737-800 varies between each flight stage. On average, the CFM56 engines of the B737-800 consume 5.41 kg of jet fuel per NM. This results in a total fuel consumption for the RNAV approach (from RIVER to the runway) of 341.9 kg, 340.8 kg for the RNP approach, and only 273.7 kg for the RNP AR approach. To convert the fuel consumption per NM to CO_2 emissions per approach, the 'ICAO Carbon Emissions Calculator' (3.4) is used, which is a proven method to calculate the precise average emissions in the aviation sector. An average load factor of 85% is assumed. This resulted in 918.3 kg of CO_2 emissions for the RNAV approach, 915.4 kg for the RNP approach, and only 735.2 kg for the RNP AR approach. This concludes that operating according to RNP AR approach procedures at runway 18R at EHAM has a big positive environmental impact on the operation, compared to RNAV or RNP procedures. This impact will result in substantial annual fuel savings for airlines operating RIVER approaches at EHAM.

Table 4.3.7: Fuel consumption and CO_2 emissions of the RNAV, RNP and RNP AR approach simulations

	Fuel Consumption (kg)	CO_2 Emissions (kg)
RNAV	341.9	918.3
RNP	340.8	915.4
RNP AR	273.7	735.2

Key Takeaways of Sub-Chapter 4.3

Section	Main Takeaways
Waypoints & Restrictions	RNAV simulation → RNAV night transition for 18R RNP simulation → RNP night transition for 18R RNP AR simulation → KLM 2023 RNP AR trails for 18R
Track Miles	RNAV: 63.2 NM, RNP: 63.0 NM, RNP AR: 50.6 NM
Fuel Consumption	RNAV: 341.9 kg , RNP: 340.8 kg, RNP AR: 273.7 kg
CO_2 Emissions	RNAV: 918.3 kg, RNP: 915.4 kg, RNP AR: 735.2 kg
Overall	RNP vs RNP AR → -19.7% track miles, fuel & CO_2 (RIVER)

4.4 Concept of Operations

This sub-chapter will answer the fourth research question, thus delving into the implementation requirements of RNP AR, analysing their achievability, and constructing a feasible concept of operations including the most suitable RNP AR implementation roadmap for EHAM.

4.4.1 Implementation & Achievability

The following section will elaborate on the three implementation requirements which enable RNP AR and EoR operations, and on the achievability of implementing these RNP AR enablers at EHAM.

4.4.1.1 Implementation Requirements

Operating RNP AR approach procedures has three main requirements. The first requirement for operating RNP AR approaches is to implement FARs. The existing airspace structure at EHAM has remained the same for several years, with FARs beginning at the IF of the IAP (LVNL, 2024). To eventually enable RNP AR operations, it is essential to extend these procedures both laterally and vertically, all while preserving capacity and safety. Currently, the FARs at EHAM start at the IF at 9.4 NM and 2000ft from the runway THRE, as is shown in Figure 4.4.1 (MovingDot, 2024). For the initial step of implementing FARs at EHAM, it is not necessary to define the FARs starting from the IAF. Instead, FARs could be designed between the IF and the IAF. For example, at 4000 ft or 6000 ft, as illustrated in Figure 4.4.1.

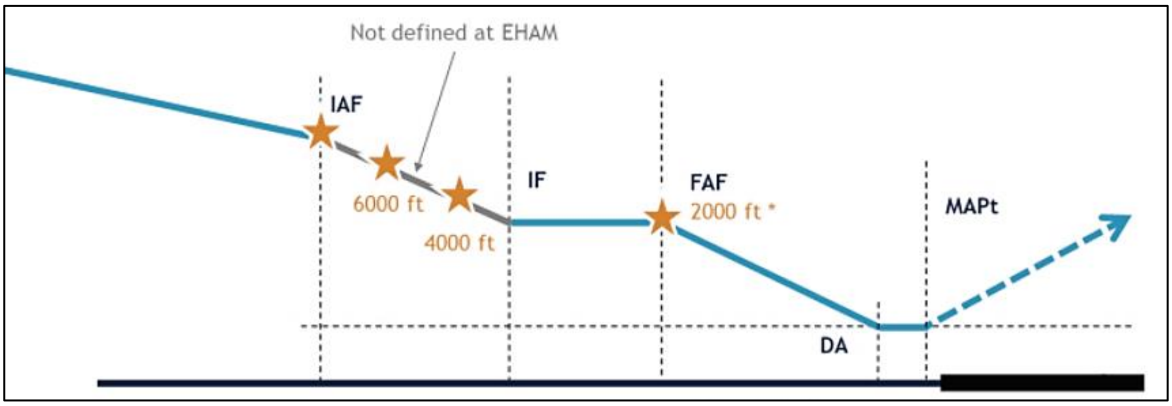

Figure 4.4.1: Future FAR implementation at EHAM (MovingDot, 2024)

Next to FARs, the implementation of CDOs at EHAM is crucial for the transition to RNP AR. CDOs aim to optimize the descent path of aircraft, minimizing both fuel consumption and emissions (ICAO, 2010). Presently, at EHAM, CDOs are limited to the IF. Extending the CDOs beyond the IF could offer advantages to airlines, potentially enhancing operational efficiency (MovingDot, 2024). CDOs are therefore related to the lateral path of RNP AR approaches. EHAM could initiate the FARs and CDOs from altitudes of 4000 ft or 6000 ft, as illustrated in Figure 4.4.2.

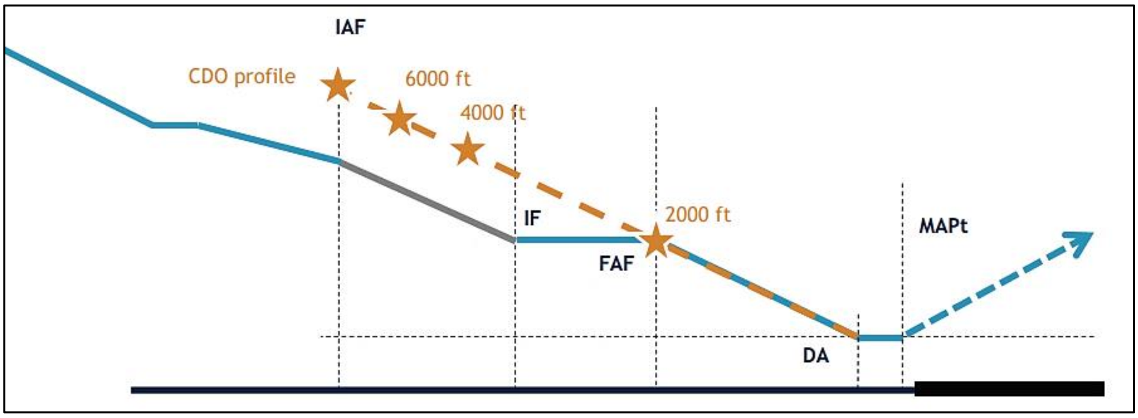

Figure 4.4.2: Future CDO implementation at EHAM (MovingDot, 2024)

Lastly, when looking at independent parallel operations, implementing EoR to enable parallel RNP AR approaches is essential. EoR is the only method capable of eliminating the separation (1000 ft / 3 NM) required for independent parallel operations before aircraft are aligned with the RNP AR final approach track. Introducing EoR at EHAM requires the availability of separation-independent operations at the airport (EUROCONTROL, n.d.). An example of single runway EoR operations, enabled by separation-independent operations, for runway 18R at EHAM, is shown in Figure 4.4.3. Separation-independent operations guarantee separation for base legs and final approaches, eliminating the need for air traffic controllers to apply extra horizontal or vertical separation measures (LVNL, 2023). However, its deployment is dependent on meeting the other two requirements of RNP AR implementation: FARs and CDOs.

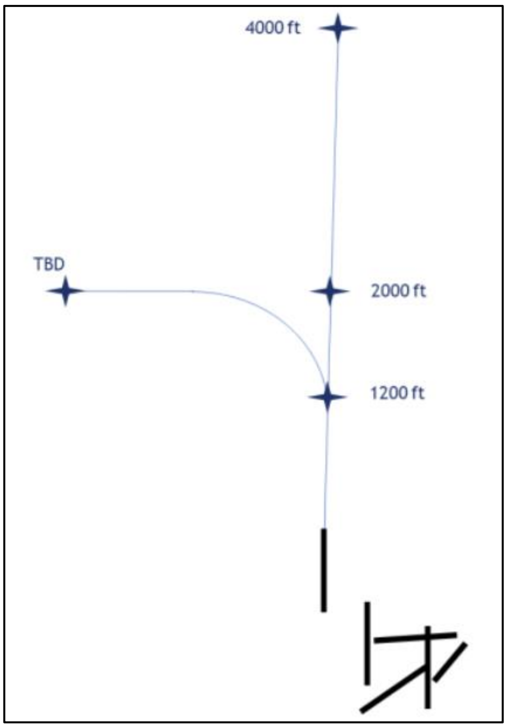

Figure 4.4.3: Future EoR implementation for runway 18R at EHAM (EUROCONTROL, n.d.)

This section concluded that the three implementation requirements for transitioning to a full RNP AR operation at EHAM (FARs, CDOs and separation-independent operations) are related to each other and that the required 1000 ft / 3 NM separation cannot be detached without the implementation of EoR operations. Thus, the design of FARs is considered crucial for the RNP AR roadmap for EHAM.

4.4.1.2 Achievability of Goal

The achievability and operational effect of transitioning to a full RNP AR operation at EHAM is based on relevant prerequisites, assumptions and constraints, from the perspective of the different research areas.

The perquisites include a stable runway configuration at EHAM (4.1.2) and appropriate merging support during mixed-equipment operations for air traffic controllers (4.2.1). The assumptions include compliance with relevant RNP AR regulations, such as EU 965 (EASA, 2021), the feasibility of independent parallel operations with other approach procedures and the presence of an appropriate FARs strategy at EHAM. The constraints include the RNP AR equipage rate of the fleet operating at EHAM (4.2.2), the flight crew RNP AR training and certification, the availability of required new ATC procedures, the approval from the regulator for these new procedures, and possible new ATC system requirements.

Regulatorily, there are no restrictions preventing the implementation of RNP AR at EHAM. All the required enablers of RNP AR operations (FARs, CDOs, and separation-independent operations) can be realized when following regulations. Apart from the operational considerations around RNP AR, there is a necessity to establish approval and authorization procedures, aligning with ICAO and EASA regulations. National authorities are responsible for creating a regulatory framework to facilitate this process (I&W, 2020).

A main aspect of the achievability of RNP AR operations is upholding the airport and airspace capacity at maximum levels because no influence on the airport and airspace capacity is acceptable during the transition process. Based on the airspace capacity analysis (4.1.3), it is expected that keeping the current capacity is achievable. To achieve this, certain actions must be taken towards the preparation of the airspace around EHAM and around air traffic controllers (4.2.1) operating RNP AR approaches (LVNL, 2024).

The airlines operating at EHAM also play a considerable role in the achievability of a full RNP AR operation at EHAM (4.2.2). Currently, the airlines are preparing to support RNP AR at EHAM by increasing RNP AR approach capability in their fleet and licensing their flight crew (KLM, 2023).

4.4.2 RNP AR Roadmap

The following section will present and explain the RNP AR roadmap which is constructed for EHAM, including additional clarification on the starting point of the roadmap and the different development phases.

4.4.2.1 Beginning of Roadmap

Taking into account the experiences and insights compiled from all stakeholders engaged at EHAM, alongside the analyses conducted in prior sections of this research, the most suitable starting point of the RNP AR roadmap for EHAM is chosen. This starting point is dependent on the factors and considerations below.

First of all, beginning the implementation of RNP AR approaches at EHAM for one runway or two runways. Based on LVNL's experience in implementing new procedures and separation methods at EHAM, it is advised to start with one runway (LVNL, 2024). This approach serves as a trial period for all stakeholders involved (the airport, air traffic controllers, and pilots) to adjust to RNP AR approach procedures. Beginning with one runway also mitigates potential safety implications on EHAM operations.

Secondly, the first runway to implement RNP AR. One of the main benefits of RNP AR is independent parallel operations. Therefore, when choosing which runway should be the first to implement RNP AR, the four runways used in parallel operations at EHAM (36R, 36C, 18R and 18C) should be considered. The analysis of the runway usage at EHAM (4.1.2) shows that the combination 18R & 18C would have greater benefits for single and parallel operations. So, for the beginning of the RNP AR roadmap, the combination of runways 18R and 18C will be used.

Finally, it needs to be determined which of these two runways goes first. Based on the characteristics of 18R and 18C and on their overall runway use, which is shown in Table 4.4.1, the best runway for the first RNP AR approach implementation at EHAM would be runway 18R. This is the beginning of the RNP AR roadmap for EHAM.

Table 4.4.1: Benefits of the two most feasible runways to start implementing RNP AR at EHAM (Schiphol, 2023)

Runway 18C	Runway 18R
4th Highest % Usage	Highest % Usage
Taxi Time	Noise Pollution
	Track Miles (RIVER)

4.4.2.2 Roadmap Path

Following the decisions outlined in the previous sections, a phased roadmap illustrating an implementation path is created. The roadmap includes all necessary steps towards realizing the main objective of this research: transitioning to a complete RNP AR operation at EHAM. The timeline of the RNP AR roadmap is indicated in years. The starting year of the roadmap is completely dependent on the implementation of FARs / CDOs at EHAM. Currently, it is not known when FARs / CDOs will be operational at EHAM. So, there is no starting year defined in the RNP AR roadmap for EHAM.

Because of the substantial amount of runways available at EHAM, it is proposed to split the roadmap and the implementation of RNP AR approach procedures into two phases. Phase 1 includes parallel runways 18R & 18C and runway 06 for converging approaches. Phase 2 includes parallel runways 36R & 36C and runway 27 for converging approaches. Figure 4.4.4 shows an overview of the entire RNP AR roadmap for EHAM, including a separation between phase one and phase two. The following two sections of this research will further elaborate on the choices made for the roadmap, concerning the runways and implementation timeline.

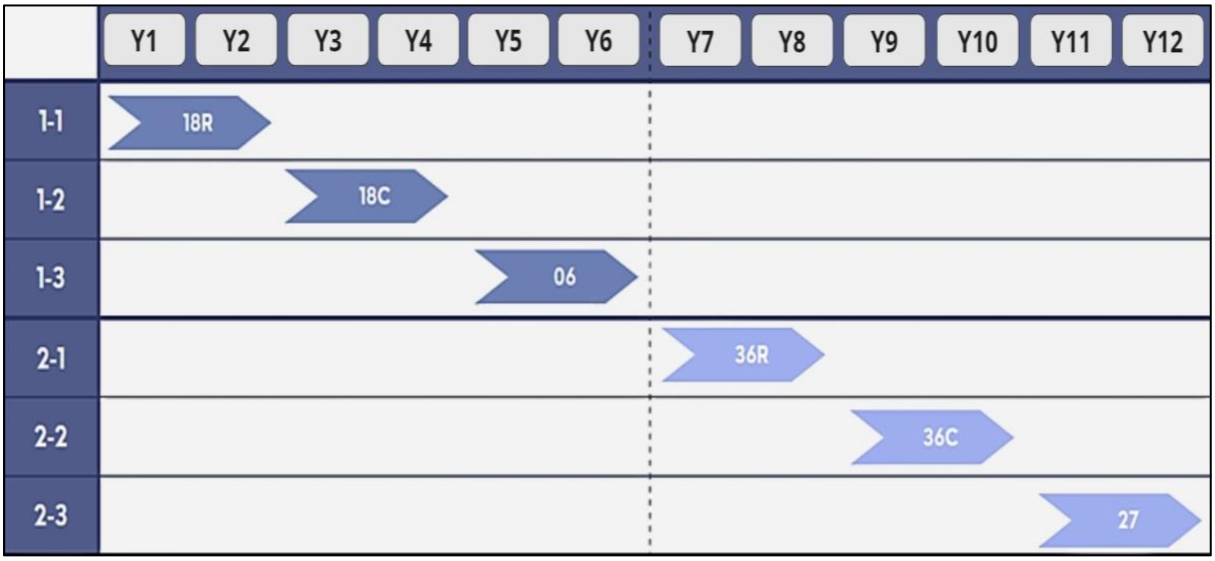

Figure 4.4.4: RNP AR implementation roadmap for EHAM

4.4.2.3 Phase One

The first part of phase one of the RNP AR roadmap for EHAM consists of designing and implementing RNP AR approaches for runway 18R. The initial approach segment of this RNP AR approach could be based on a straight-in approach in combination with a short final approach from the North Sea Canal, similar to the RNP AR approach designed for the KLM trials in 2023 (4.2.2.6) and similar to the RNP AR approach simulation flight track (4.3.2.2). The design and implementation of an RNP AR approach procedure for runway 18R has various dependencies. For example, the procedure needs a FAR / CDO combined with an RNP AR approach procedure design (LVNL, 2024). Additionally, an approval process is necessary by ILT (Human Environment & Transport Inspectorate), because this would be the first RNP AR approach procedure in the Netherlands (ILT, 2024). Also, it is recommended to have an evaluation period of at least around half a year after the implementation, where the differences between the expectations and realizations of the stakeholders can be assessed. Design changes may be needed after its first design to meet the design requirements of the next steps in the RNP AR roadmap, especially for parallel operation with 18C.

The second part of phase one of the RNP AR roadmap for EHAM consists of designing and implementing RNP AR approaches for runway 18C. Next to the goal of this research, transitioning to a complete RNP AR operation, it is also feasible to implement EoR operations, enabled by RNP AR. Hence, an additional RNP AR approach procedure would be necessary for runway 18C. It is advisable to initiate the design of the RNP AR approach to runway 18C once the design and initial evaluation period of the RNP AR approach to runway 18R is concluded. The development of the RNP AR approach for runway 18C introduces a new opportunity: conducting EoR operations with two RNP AR approach procedures, capitalizing on the advantages of FAR, CDO, and separation-independent operations simultaneously. However, executing EoR operations with two RNP AR approach procedures necessitates an additional safety case addressing GNSS failure (ICAO, 2021).

The third and final part of phase one of the RNP AR roadmap for EHAM consists of designing and implementing RNP AR approaches for runway 06. Runway 06, among the top three runways in average usage at EHAM, gains from the RNP AR implementation in single runway and converging operations scenarios. The design and implementation of this RNP AR approach procedure mostly depend on previous considerations at runways 18R and 18C. An RNP AR approach for runway 06 is only applicable to single and converging runway operations, thus it does not affect EoR operations. For such operations, similar prerequisites and constraints as the prior runways apply regarding system support and mixed equipment (LVNL, 2024). For each part of phase one, a period of two years is suggested. This is sufficient time to design, implement, operate and evaluate one RNP AR approach procedure per runway.

4.4.2.4 Phase Two

Before advancing to the second phase of the RNP AR implementation roadmap, it is crucial to assess whether the already implemented RNP AR procedures and EoR operations align with the predefined requirements and objectives concerning capacity, safety, and efficiency. It is advisable to engage all stakeholders in this evaluation process. If the evaluation has positive results, it is advised to follow a comparable RNP AR implementation roadmap and timeline for the remaining three runways: 36R, 36C, and 27, as shown in Figure 4.4.5.

Key Takeaways of Sub-Chapter 4.4

Section	Main Takeaways
Implementation Requirements	RNP AR enablers: FARs + CDOs EoR enabler: separation-independent operations
Achievability of Goal	Perquisites: runway configuration + merge support Assumptions: regulatory compliance + handling mixed traffic + FARs strategy Constraints: system requirements + equipment rate + flight crew training + authorities approval
Beginning of Roadmap	Most benefits → parallel runway → most used → 18R
Roadmap Development	Phase 1: 18R → 18C → 06 Phase 2: 36R → 36C → 27 Two years per runway implementation

5. Conclusion

At present, there are no RNP AR approach procedures available at EHAM. LVNL would like to implement RNP AR at EHAM because of the optimization benefits regarding the efficiency and safety of approaches. However, RNP AR approach procedures have different requirements and constraints compared to the current IAPs operated at EHAM. Especially in terms of airspace, airport, air traffic controller, aircraft and flight crew requirements.

The goal of this thesis was to provide advice to LVNL and the KDC on the feasibility and achievability of the implementation of RNP AR approach procedures at EHAM. To reach this goal, the following main research objective was constructed: '*Determine the feasibility and achievability of transitioning to a full RNP AR operation at EHAM while maintaining maximum capacity, by constructing a concept of operations including an RNP AR roadmap, based on relevant airspace, airport, capacity, ATC and airline analyses.'* To achieve this main objective, qualitative and quantitative research has been performed, according to the methodological approach (3.1).

The airspace analysis showed that adapting to a future mixed-equipment operation with different RNP AR and non-RNP AR separation buffers, semi-width and buffer zones is crucial to maintain maximum efficiency. The airport analysis showed that implementing RNP AR procedures at every runway should be achievable and emphasized the importance of parallel runway availability for future EoR operations. The airspace capacity analysis concluded that implementing RNP AR at EHAM could slightly improve the airspace capacity at EHAM. RNP AR approaches are less optimal than ILS approaches regarding approach capacity, but this can be prevented by using RNP AR with ILS approaches. Also, it concluded that designing RNP AR procedures for EoR operations at EHAM could allow for slightly reduced runway buffers. Additionally, the capacity analysis showed that RNP AR approaches have similar effects on visibility capacity levels as ILS approaches.

The ATC analysis concluded that LVNL is not yet capable of operating a complete RNP AR operation at EHAM. The RECAT-EU separation standards for the current IAPs at EHAM also count for RNP AR procedures, so this will not affect the operational capacity of LVNL. Furthermore, the analysis showed that the TMA management of LVNL will have to change from primarily vectoring, to operating FARs and shifting to speed control only. Due to the complexity of this transition and the introduction of a mixed-equipment operation, it is crucial to provide merging assistance to air traffic controllers. The airline analysis concluded that the airlines are not yet fully RNP AR capable, but are on track to achieve this in the proposed timeline. The overall aircraft RNP AR capability at EHAM is risen from 10.1% to 21.9% between 2017 and 2024, due to aircraft renewal strategies of the big airlines operating at EHAM. In the upcoming years, these airlines will continue to innovate their fleet, resulting in a total fleet RNP AR capability at EHAM of around 80% in 2028.

The approach simulations illustrated that an RNP AR approach for runway 18R at EHAM has significant environmental benefits for airlines in terms of reduced track miles, fuel consumption and CO_2 emissions. When considering RIVER as the starting point of the approach procedure, the track miles, fuel consumption and CO_2 emissions of the RNP AR approach were reduced by 19.7% compared to the RNP approach. The ConOps concluded that the enablers of RNP AR could be implemented at EHAM without constraints and in the proposed timeframe. FARs, CDOs and separation-independent operations are all achievable at EHAM, within relevant regulations. The most feasible starting point of the RNP AR roadmap is 18R. Additionally, the development of the roadmap can be best split up into phases, each consisting of six years and three runways.

To conclude, the operational and environmental benefits of RNP AR approaches make the transition to a full RNP AR operation at EHAM feasible for all stakeholders involved: EHAM, LVNL and the airlines. Furthermore, after adapting to adequate RNP AR requirements, all stakeholders will be able to operate a full RNP AR operation within the proposed timeframe, making the transition to a full RNP AR operation at EHAM achievable.

6. Recommendations

This research aims to investigate the feasibility and achievability of transitioning to a full RNP AR operation at EHAM. This chapter makes specific recommendations for the stakeholders involved (6.1) and recommends potential future research (6.2).

6.1 Stakeholder Recommendations

The following recommendations are made for LVNL.

- Transition to operating completely according to RNP AR approach procedures at EHAM by implementing RNP AR and eventually EoR, according to the implementation steps and timeline of the concept of operations and RNP AR roadmap for EHAM.
- Implement FARs / CDOs at EHAM, which will change the main approach strategy of LVNL from primarily vectoring to fixed approaches. But, let air traffic controllers maintain speed control over aircraft to ensure maximum capacity levels and uphold appropriate separation.
- When designing new RNP AR approach procedures for EHAM, overlay these fixed arrival routes with current common vector patterns to improve the acceptance of air traffic controllers and to facilitate a smooth workload transition.
- Distinguish and communicate clear differences between RNP AR routes and vector patterns to air traffic controllers and flight crew to prevent any misunderstandings.
- Perform regular safety assessments on the handling of mixed-equipped aircraft at EHAM during the first implementation phase of the RNP AR roadmap. These assessments provide potential improvements for the second implementation phase.
- Apply a 'best equipped / best served' principle during the mixed-equipment phase. RNP AR capable aircraft will be granted priority before non-RNP AR capable aircraft (which are vectored). This will stimulate airlines to innovate their fleet with RNP AR capable aircraft.
- Develop (digital) merging support tools for air traffic controllers to easily identify if approaching aircraft are RNP AR capable or non-RNP AR capable.
- Implement and execute a training program for all (new) air traffic controllers which incorporates all relevant design and operational requirements of RNP AR approach procedures.
- Stay in close contact with all other stakeholders involved on possible changes in their runway development (EHAM) and their fleet renewal strategies (airlines).

The following recommendations are made for national and international aviation authorities.

- Define a standard national approach for the approval of RNP AR approaches at EHAM to speed up the approval process and minimize impacting capacity levels at the airport.
- Further outline requirements for future (parallel) EoR operations at EHAM.
- When deciding on approving RNP AR approach procedures at EHAM, consider comparable approvals from other European countries and the United States, which already have RNP AR implemented.

The following recommendations are made for the airlines operating at EHAM.

- Prioritize having a fleet renewal strategy focused on transitioning to operating completely according to RNP AR approach procedures.
- Concentrate on replacing non-RNP AR capable aircraft with RNP AR capable aircraft, instead of retrofitting already owned aircraft with RNP AR systems.
- Develop a training program for all (new) flight crew which incorporates all relevant design and operational requirements of RNP AR approach procedures.

The following recommendations are made for EHAM.

- Develop a runway strategy which ensures a smooth transition to mostly RNP AR capable aircraft approaching the airport.
- Communicate closely with LVNL to prevent major runway maintenance during critical periods of the RNP AR implementation steps. This could obstruct the development of parallel RNP AR approaches and EoR operations.

6.2 Future Research

Future research could be performed on several relevant topics which were out of the scope of this research. For example, research could be continued in iLabs on the impact of implementing RNP AR approach procedures on the noise pollution around EHAM. By using ECAC Doc.29, exact noise level differences between certain IAPs at EHAM could be calculated. Also, it could be concluded precisely which neighbourhoods under the approach flight paths benefit or feel a drawback of the transition to a full RNP AR operation at EHAM.

Furthermore, the input for the iLabs simulations in this research were assumed waypoints, based on comparable approaches or trials at EHAM. Future research could investigate constructing detailed designs for FARs / CDOs, including RNP AR approach procedures.

Lastly, this research focused mostly on the feasibility and achievability of transitioning to a full RNP AR operation at EHAM, taking EoR into account as a secondary topic. Research could be continued around Established on RNP in combination with RNP AR to maximize the benefits of RNP AR approach procedures regarding independent parallel operations at EHAM.

7. Personal Reflection

During the finalization of a project of this scale, it is important to reflect on how the research proceeded. The STARR method is an appropriate reflection method and is used to review this research. The STARR method consists of five sections: Situation, Task, Action, Result and Reflection. With each part analysing a specific section of the research process.

The situation which is investigated is LVNL wanting to implement RNP AR approach procedures at EHAM because of the optimization benefits for stakeholders concerning the efficiency and safety of approaches. However, it was unknown if transitioning to a full RNP AR operation is feasible and achievable in a suitable timeline for the major stakeholders: EHAM, LVNL and the airlines. So, the task was to bring clarity to these uncertainties. In order to fulfil these tasks, an advisory thesis report is written on the most suitable approach to achieve a complete RNP AR operation at EHAM. A structured Gantt chart planning made sure all research was done on time. This action plan resulted in a thesis, consisting of four research areas, which has achieved the main research objective by analysing the airspace and airport characteristics, the airspace capacity, the capabilities of and impact on LVNL and the airlines, and by simulating IAPs and constructing a concept of operations for EHAM.

When reflecting on the results of this thesis, the chosen research methods were suitable for achieving the wanted results. By following the methodological approach and using the appropriate research methods, relevant results were ensured which helped achieve the objectives. The end goal of this project was to provide advice to LVNL and the KDC on the feasibility and achievability of transitioning to a full RNP AR operation at EHAM. This thesis succeeded in doing so. Especially the concept of operations, including the RNP AR roadmap for EHAM, has given LVNL and the KDC a clear illustration of the implementation capabilities over time.

The overall time management during the project went well and structured. But, personal productivity could be improved when comparing the very productive first and last weeks of the project with the less productive middle months. One personal aspect which could be considered to be in need of improvement is involving more people in my project. Except for the short interviews, I was doing research by myself, instead of including people with relevant expertise in the topics in my project. Next project, I would like to improve on this aspect.

This research experience has enriched me with lots of relevant academic knowledge on Performance Based Navigation and specifically Required Navigation Performance Authorization Required. I have gotten a much better comprehension of the cooperation between the stakeholders at Schiphol Airport, and of their main characteristics, responsibilities and future plans.

Overall, I am grateful for getting the chance to perform my internship and graduating at Air Traffic Control the Netherlands and the Knowledge & Development Centre Mainport Schiphol, which is an exceptional combination. This opportunity provided me with unique insights into the current Dutch aviation ecosystem and the ongoing developments at the KDC partners.

8. Bibliography

Amai, O., & Matsuoka, T. (2015). *Air Traffic Control Real-time Simulation Experiment regarding the Mixed Operation between RNP AR and ILS Approach Procedures*.

Boeing. (2006). *Flight Planning and Performance Manual B737-800.*

Boeing. (2011). *Boeing and Lion Air pioneer precision satellite navigation technology*. https://boeing.mediaroom.com/2011-10-05-Boeing-and-Lion-Air-Pioneer-Precision-Satellite-Navigation-Technology

EASA. (2017). *Annex IV – Part-ATS: Technical Requirements for Providers of Air Traffic Services. https://www.easa.europa.eu/en/document-library/easy-access-rules/online-publications/easy-access-rules-atm-ans-regulation-eu?page=24*

Entzinger, J., Nijenhuis, M., Uemura, T., & Suzuki, S. (2013). *Assessment of Human Pilot Mental Workload in Curved Approaches*.

EUROCONTROL. (2020). *European Continuous Climb and Descent Operations Action Plan.*

EUROCONTROL. (2020). *European PBN Route Spacing Handbook (No. 3).*

EUROCONTROL. (n.d.) CNS Dashboard on PBN Capabilities: Aircraft (Public Data). https://ext.eurocontrol.int/analytics/saw.dll?Dashboard

EUROCONTROL. (n.d.). *Performance Based Navigation Portal*. https://pbnportal.eu/epbn/home/home.html

European Commission. (2018). Commission Implementing *Regulation (EU) 2018/1048 of 18 July 2018 http://data.europa.eu/eli/reg_impl/2018/1048/oj*

FlightAware. (2024). *Instrument Approach Availability for the runways at EHAM.*

GCP. (2023). *Annual CO_2 Emissions per Country 2023.*

Guo, D., & Huang, D. (2020). *PBN Operation Advantage Analysis over Conventional Navigation*.

Hanses, C., & Korn, B. (2015). *Designing Segmented Independent Parallel Approach Procedures for a Mixed-Equipage Environment.*

I&W. (2020). *Regeling Boorduitrusting BWBROO12538.*

I&W. (2020). *Verantwoord vliegen naar 2050 – Luchtvaartnota 2020-2050.*

I&W. (2021). *Performance Based Navigation (PBN) Roadmap for the Netherlands 2020-2030.*

IATA. (2022). ICAO *Carbon Emissions Calculator (ICEC).*

IATA. (2024). *Jet Fuel Price Monitor.*

ICAO. (2010). *Doc 9931 – Continuous Descent Operations (CDO) Manual (First Edition).*

ICAO. (2016). *Doc 4444 – Procedures for Air Navigation Services Air Traffic Management (16th Edition).*

ICAO. (2016). *Doc 9750 – 2016-2030 Global Air Navigation Plan (Fifth Edition*).

ICAO. (2019). *Assembly – 40th Session: Efficiency in Air Traffic Management through Required Navigation Performance Authorization Required (RNP AR).*

ICAO. (2020). *Doc 8168 – Procedures for Air Navigation Services Aircraft Operations (Seventh Edition)*.

ICAO. (2020). *Doc 9643 – Manual on Simultaneous Operations on Parallel or Near-Parallel Instrument Runways (SOIR) (Second Edition).*

ICAO. (2021). *Doc 9905 – Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual (Third Edition)*.

ICAO. (2021). *EUR Doc 025 – EUR RNP APCH Guidance Material.*

ICAO. (2023). *Doc 9613 – Performance-based Navigation (PBN) Manual (Fifth Edition)*.

ILT. (n.d.) *Over de ILT.* https://www.ilent.nl/over-ilt

KDC. (2013). *Continuous Descent Operations (CDOs) from low altitudes to parallel runways 18R and 18C*.

KDC. (2020). *Adviesdocument implementatiestrategie voor de transitie naar een VNR ATM systeem*.

KLM. *(2023). EHAM RNP AR trials 18R.*

KLM. *(2023). RNP AR Fleet Equipage.*

KLM. (2024). *Flight Crew RNP AR Experience, Knowledge and Preferences.*

LVNL. *(2023). Baancombinaties en Zicht 2016 t/m 2023.*

LVNL. (2024). *AIP Netherlands.* https://eaip.lvnl.nl/web/2024-05-30-AIRAC/html/index-en-GB.html

LVNL. (2024). *Interviews with various air traffic controllers of Air Traffic Control the Netherlands.*

Mayer, R., Crow, B., Zondervan, D., & Allerdice, J. (2015). *Concept and Benefits of PBN-Enabled Parallel Approach Operations*.

McDonald, J., & Kendrick, J. (2008). *Benefits of Tightly Coupled GPS/IRS for RNP Operations in Terrain Challenged Airports*.

Medeiros, D., Silva, J., & Bousson, K. (2012). *RNAV and RNP AR Approach Systems: The case for Pico Island Airport*.

Miller, S., & Bruce, J. (2011). *Integration of the "Constant Radius Arc to a Fix" (RF) Navigation Leg type into NextGen.*

Morscheck, F. (2018). *Noise Mitigation Optimization of A-RNP /RNP AR Approaches*.

Morscheck, F. (2020). *The Influence of Shape and Density of exemplary City Areas on the Possible Benefit of optimized Noise Abatement A-RNP and RNP-AR Procedures*.

Moving Dot. (2020). *PBN Roadmap for the Netherlands 2020-2030.*

Moving Dot. (2024). *Implementation of Established on RNP APCH Procedures at EHAM.*

NLR. (2022). *Feasibility study on Parallel Approaches at Schiphol using Established on RNP*.

Post J., (2024). *LVNL Waypoints Database (Excel File)*

Post J., (2024). *RNAV Approach 18R Simulation Input (Excel File).*

Post J., (2024). *RNP Approach 18R Simulation Input (Excel File).*

Post J., (2024). *RNP AR Approach 18R Simulation Input (Excel File).*

Savas, T., & Sahin, O. (2017). *Safety Assessment of RNP AR Approach Procedures*.

Schiphol. (2024). *Traffic reviews 2019 t/m 2023.*

Schiphol. (2023). *Gebruiksprognose 2024.*

Unkelbach, R., & Dautermann, T. (2021). *Development and Evaluation of an RNP AR Approach Procedure under Tight Airspace Constraints*.

9. List of Appendices

Appendix A: iLabs Approach Simulations Coding (4.3.1)

```
import pandas as pd

import mpu

wpts = pd.read_csv('LVNL_wpts.csv') wpts


data = pd.read_excel('STIJN_RNPAR.xlsx')

data['lat'] = 0

data['lon'] = 0

data['dist'] = 0


for i in range(len(data)):

    data.lat.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lat

    data.lon.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lon


for i in range(len(data)-1):

    data.dist.iloc[i+1] = data.dist.iloc[i] +
mpu.haversine_distance((data.lat.iloc[i], data.lon.iloc[i]),
(data.lat.iloc[i+1], data.lon.iloc[i+1]))


print('total dist is ' + str(data.dist.iloc[-1]) + ' km')

data.to_excel('STIJN_RNPAR.xlsx')


data = pd.read_excel('STIJN_RNP.xlsx')

data['lat'] = 0

data['lon'] = 0

data['dist'] = 0
```

```
for i in range(len(data)):

    data.lat.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lat

    data.lon.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lon


for i in range(len(data)-1):

    data.dist.iloc[i+1] = data.dist.iloc[i] +
mpu.haversine_distance((data.lat.iloc[i], data.lon.iloc[i]),
(data.lat.iloc[i+1], data.lon.iloc[i+1]))


print('total dist is ' + str(data.dist.iloc[-1]) + ' km')

data.to_excel('STIJN_RNP.xlsx')


data = pd.read_excel('STIJN_RNAV.xlsx')

data['lat'] = 0

data['lon'] = 0

data['dist'] = 0


for i in range(len(data)):

    data.lat.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lat

    data.lon.iloc[i] = wpts.loc[wpts.name == data.iloc[i].WP].lon


for i in range(len(data)-1):

    data.dist.iloc[i+1] = data.dist.iloc[i] +
mpu.haversine_distance((data.lat.iloc[i], data.lon.iloc[i]),
(data.lat.iloc[i+1], data.lon.iloc[i+1]))


print('total dist is ' + str(data.dist.iloc[-1]) + ' km')


data.to_excel('STIJN_RNAV.xlsx')
```

Intern

Samen luchtvaart mogelijk maken

Air Traffic Control the Netherlands

Stationsplein Zuid-West 1001
1117 CV Schiphol

PO Box 75200
1117 ZT Schiphol
The Netherlands

T +31 (0)20 406 2000

www.lvnl.nl