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VLD3-W2-SORT

SAFELY OPTIMISED RUNWAY THROUGHPUT

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Abstract

The present document constitutes the Demonstration Report (DEMOR) Part I, hence is the core part of the contractual deliverable (D1.4), of the SESAR 2020 project VLD3-W2-SORT. This document comprises an overview of the executed demonstration activities and other main results within the project. It provides a comprehensive description of the exercises performed followed by an analysis of the results obtained. Furthermore, the objectives defined in the corresponding Demonstration Plan (Contractual Deliverable D1.1) are reviewed and documented.

This final version of the DEMOR is composed of five different parts, named Part I, II, III, IV and V. Part I is the core text that provides an overview all exercises performed and all SESAR Solutions involved. It describes the results on the pre-industrialisation activities performed for the *optimized wake separation for arrivals with Minimum Radar Separation (MRS) and enhanced Runway Occupancy Time (ROT) simulations*, so called *wake decay enhancing devices* and furthermore on the outcome of the *Integrated Runway Sequence Function (IRSF) experiment*. Part II deals with the Safety aspects of the Solutions, Part III covers the Human Performance, Part IV the Environmental Assessment and Part V the Performance Assessment. It is noted that for the pre-industrialisation development work only the Part I, II and IV contributions have been set up.

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1 Executive summary

The document constitutes the Demonstration Report (DEMOR)-Part I, i.e., the contractual deliverable D1.4, of the SESAR2020 project VLD3-W2-SORT.

This document comprises an overview of the executed demonstration activities and other main results within the project. It provides a comprehensive description of the exercises performed followed by an analysis of the results obtained. Furthermore, the objectives defined in the corresponding Demonstration Plan (i.e., Deliverable D1.1, applied version released as D1.1.04) [5] are reviewed and documented.

The current, second version of the DEMOR, is released as contractual deliverable D1.4. It is composed of five different parts, consists of the Parts I, II, III, IV and V. Part I is the core text that provides an overview of all exercises and main activities performed and all SESAR Solutions involved. The main results described are:

- the results of the *Pairwise separation, including ROT elements and MRS*, validation exercise;
- the results on the pre-industrialization activities performed for the so called *wake decay enhancing devices*, and
- on the experimental outcome of the *Integrated Runway Sequence Function (IRSF)* shadow mode demonstration.

Part II deals with the Safety aspects of the Solutions, Part III covers the Human Performance, Part IV the Environmental Assessment and Part V the Performance Assessment. It is noted that for the pre-industrialization development work only the Part I, II and V contributions have been set up.

2 Introduction

2.1 Purpose of the document

This document constitutes the Demonstration Report (DEMOR-Part I), hence is the core part of the contractual deliverable D1.4, of the SESAR2020 project VLD3-W2-SORT. This document comprises an overview of the results of the executed exercises and other main activities performed as part of this project. Furthermore, the objectives defined in the corresponding Demonstration Plan (DEMOP) [5] are reviewed and documented.

2.2 Scope

This is the DEMO Report for VLD3-W2-SORT in which the main results of the exercises and key activities are further detailed.

2.3 Intended readership

The intended readers of this document are the VLD3-W2-SORT team members working on the demonstrations and other main activities, the SESAR Joint Undertaking (SJU) and SESAR community. Furthermore, anybody with a sincere interest in Air Traffic Management (ATM) research and ATM operations is invited to read the report.

More specifically, this document is written and edited for this use by SESAR2020 VLD3-W2-SORT partners.

Internal to SESAR2020 and VLD3-W2-SORT it will

- Provide the results on the various demonstration exercises.
- Provide an overview of the other main project activity outcomes.

External to SESAR2020 and VLD3 SORT.

- ANSPs - Learn about benefits of Pairwise Time-Based Separation with improved ROT management and support for reduced MRS, as well as on advantages and implication of the Integrated Runway Sequence Function and concept. Furthermore, learn about the safety gains and potential capacity gains that can be brought along by the installation of wake decay enhancing devices.
- Airports – Learn about benefits of Pairwise Time-Based Separation with improved ROT management and support for reduced MRS, as well as on the implication of the Integrated Runway Sequence Function and concept. Furthermore, they can learn about the safety gains and potential capacity gains that the wake decay enhancing devices installed in the approach area of an airport potentially could make available.
- Airlines – Learn about the benefits of Pairwise Time-Based Separation, particularly with regards to the improved ROT management and support for reduced MRS, while demonstrating

the value of complying with ATC speed instructions on final approach and vacating the runway as soon as operationally possible, and on the potential arrival and departure implications of the Integrated Runway Sequence concept, as well as on the wake decay enhancing plate line installation.

- SESAR partners – interest in the demonstration of the concept and provision of evidence on the impact upon landing rates. It is expected that SESAR will focus particularly on the implementation of Solutions PJ.02-01, PJ.02-03 and PJ.02-08.

2.4 Background

The work in WP2 (supported by WP4) is being developed as an evolution of the Enhanced Time-Based Separation tool (eTBS) employed at London Heathrow Airport since 2018. The original concept for this tool was developed to a V3 maturity level in 2013 as part of SESAR PJ.06-08-01. This led to the development and deployment of an operational version of the tool using the UK 6CAT Wake Turbulence scheme at Heathrow in 2015. The TBS system was enhanced in 2018 to utilise Time-Based RECAT-EU categorisation, an Optimised Runway Delivery (ORD) tool (to enable moving delivery of separations from 4DME to Threshold) and Runway Occupancy Time (ROT), which were all validated in solution PJ.02-01-01. The evolution from eTBS to the Intelligent Approach (IA) platform, includes optimised Pairwise wake separation rules (RECAT-PWS, solution PJ.02-01-04) together with the optimised ROT Spacing rules (solution PJ.02-08-03) and the 2 NM MRS (solution PJ.02-03), and the procedural, system support and regulatory enablers required for deploying these more efficient separation and spacing rules.

In SESAR2020 WAVE-1 PJ.02-01, a wake decay enhancing device called “plate lines” (solution PJ.02-01-07) has been developed and validated to technology readiness level TRL 6 (technology demonstrated in relevant environment), in order to reduce the risk of wake vortex encounters and potentially reduce aircraft separation minima. An experimental installation of plate lines at the approach end of the runway 16 of Vienna international airport in 2019 has proven to reduce the lifetime of the longest-lived and thus potentially most hazardous wake vortices in the critical height range before touchdown. Patents on the concept/ product have been filed in several European countries, Japan and Singapore. In WP3 this concept will be further improved for (pre-) industrialisation to achieve TRL7, see [27] for the TRL7 definition.

Solution PJ.02-08 “Traffic optimisation on single and multiple runway airports” reached V3 at the end of 2019. Using this as a basis a VLD type of demonstration has been set up in WP5 to show the use of the Integrated Runway Sequence Function (IRSF) working with mixed mode operations at parallel runways (solutions PJ.02-08-01 and PJ.02-08-02), as well as some runway configurations that are frequently used in real operations at Stockholm-Arlanda. The following KPAs were addressed: capacity, environment, predictability and punctuality.

2.5 Structure of the document

The Demonstration Report (DEMOR) contractual deliverable (D1.4) is made up of 5 different parts.

- Part-I covers the main body of the Demonstration Report
- Part-II (SAR) covers the Safety Assessment Results
- Part-III (HPAR) covers the Human Performance Assessment Results (HPAR) that describes the Human Performance assessment outcome work for the SESAR Solution.
- Part IV ENVAR provides an overview of the environmental performance described by the research objectives, as described in the Demonstration Plan.
- Part V PAR covers the extrapolation to ECAC-wide level of the performance assessment results conducted from exercises performed and the process applied to obtain the results.

It is noted that the 'demonstration' results of the wake plate lines task are a pre-industrialisation of a prototype and therefore do only contribute to the Part II (SAR) and Part V (PAR).

The Part-I (this) document itself is organised as follows:

- Chapter 1 presents an executive summary of the project
- Chapter 2 gives an introduction by describing the scope, readership and structure of the document. Furthermore, some background information an overview of the terms and acronyms used in this document.
- Chapter 3 gives an overview of the Very Large Demonstrations performed. In this chapter the scope is set by the SESAR Solution(s) addressed in this VLD project. Furthermore, this chapter provides a summary of the Demonstration Plan and the operating method that is validated in the demonstrations.
- Chapter 4 presents the demonstration results. A summary of demonstration results is given followed by a detailed analysis per demonstration objective. This chapter concludes with a statement on the confidence in results of demonstration exercises.
- Chapter 5 gives an overview of conclusions and recommendations based on the results of demonstration exercises. The recommendations relate to (for example) industrialization and deployment, regulation and standardisation initiatives, and updates for the ATM Master Plan L2.
- Chapter 6 gives a summary on the Communications and Dissemination activities addressed by this VLD project.
- Chapter 7 provides an overview of referenced documents.
- Appendices A, B and C give a report per demonstration exercise.
- Appendix D provides the results of the WP4 project's technical outcome on PWS, iROT and Optimised ROT spacing principles and regulatory framework.
- Appendix E provides the final results of the WP2/WP4 ML/AI workshop study and
- Appendix F provides the WP2/WP4 related Identification of Inconsistent Aircraft Type and Registration in Flight Plans.

2.6 Glossary of terms

Term	Definition	Source of the definition
AIR-REPORT	A report from an aircraft in flight prepared in conformity with requirements for position, and operational and/or meteorological reporting.	ICAO Annex
AROT	Arrival Runway Occupancy Time	This report
iROT	Individual Runway Occupancy Time	This report
RECAT-EU	EU-proposed Wake Turbulence Re-categorisation RECAT-EU Scheme	[12]
RECAT-EU-PWS	EU-proposed Pair-Wise wake turbulence Scheme	[13]
ROCAT	ROT-based aircraft CATegorisation	This report
ORD	Refers to the Optimised Runway Delivery concept which intends to provide additional tool support to show the Controller the required spacing on the approach to take into account the effect of compression primarily caused by aircraft decelerating to land.	See Ref. [3], or OFA 01.03.01 Enhanced Runway Throughput Consolidated Final Step 1 OSED [4]
S-PWS	Refers to Static Pair-Wise Separation, a wake separation concept where wake separations are optimised by defining them between aircraft type pairs rather than between wake categories.	See Ref. [3], or OFA 01.03.01 Enhanced Runway Throughput Consolidated Final Step 1 OSED [4]

Table 1: Glossary of terms

2.7 List of Acronyms

Acronym	Definition
AAVIP	Advanced ATM Validation Integrated Platform
ACT	Activity
ADS-B	Automatic Dependent Surveillance Broadcast

Acronym	Definition
AIC	Aeronautical Information Circulars
ALDT	Actual LandIng Time
AMAN	Arrival MANager
AMC	Acceptable Means of Compliance
ANSP	Air Navigation Service Provider
AO	Airport Operations
AOBT	Actual Off-Block Time
APP	Approach
AROT	Arrival Runway Occupancy Time
ARR	Arrival
ATC	Air Traffic Control
ATCC	Air Traffic Control Centre
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATM	Air Traffic Management
ATOT	Actual Take-Off Time
ATS	Air Traffic Services
AUO	Airspace User Operations
BADA	Base of Aircraft DATA
CAP	CAPacity
CAT	CATegory
CDE	Communication, Dissemination, and Exploitation Plan
COM	COMmunications
CONOPS	Concept of Operations
CR	Change Request
CTL	Clearance To Land
CWP	Controller Working Position
DEMOP	Demonstration Plan
DEMOR	Demonstration Report
DEP	Departures
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)

Acronym	Definition
DMAN	Departure Manager
DME	Distance Measuring Equipment
DS, DS19, DS20, DS21, DS22, DS23	Dataset, Dataset number 19 till 23
E-AMAN	Extended AMAN
EASA	European Aviation Safety Agency
EATMA	European ATM Architecture
ECAC	European Common Aviation Area
EFPS	Electronic Flight Progress Strips/System
ELZ	Early Line Zero
EMT	Early Morning TEAM
ENV	ENVironment
EOC	Essential Operational Changes
EOP	End of Participation (Questionnaire)
eTBS	Enhanced Time-Based Separation
EU	European Union
EUROCONTROL	EUROPEAN ORGANISATION FOR THE SAFETY OF AIRNAVIGATION
EXCDS	Extended Computer Display System
EXE	EXercise
EXOT	Estimated taxi Out Time
FAF	Final Approach Fix
FAT	Factory Acceptance Test
FIN	FINal approach controller
FPS	Flight Progress Strips/System
FTD	Final Target Distance Indicator
GCAMS	Generic Control and Monitoring System
GS	Group Supervisor
GUID	Guidance Material
GWCS	Glideslope Wind Conditions Service
HAL	Heathrow Airport
HMI	Human Machine Interface

Acronym	Definition
HPAP	Human Performance Assessment Plan
HPAR	Human Performance Assessment Report
IA	Intelligent Approach
ICAO	International Civil Aviation Organization
IF	Intermediate Approach Fix
ITD	Initial Target Distance
INT	INTermediate approach controller
INTEROP	Interoperability Requirements
IRSF	Integrated Runway Sequence Function
KPA	Key Performance Area
Kt	Knots
LFV	LUFTFARTSVERKET
LORD	Leading Optimised Runway Delivery
LoS	Losses of Separation
LSZH	Zurich airport
LTMA	London Terminal Manoeuvring Area
LVP	Low Visibility Procedures
MATS	Manual of Air Traffic Services
MET	METeo/METeorological
METAR	Meteorological Aerodrome Report
MLAT	Multilateration
MOPs	Method of Operations
MRS	Minimum Radar Separation
NLR	Royal Netherlands Aerospace Centre
NM	Nautical Mile
NODE	NATS Operational Display Equipment
NOTAM	Notice To Airmen
OBJ	Objective
OFA	Operational Focus Area
OI	Operational Improvement
OIT	Operational Interface Testing

Acronym	Definition
OPNOT	Operational Notice
ORD	Optimised Runway Delivery
OSED	Operational Service and Environment Definition
PANS	Procedures for Air Navigation Services
PAR	Performance Assessment Report
PCP	Pilot Common Project
PfA	Proposal for Amendment
POI	Preliminary Operational Improvement
PU	Public
PWS	Pair-Wise Separation
QoS	Quality of Service
RBT	Reference Business Trajectory
RECAT-EU	European Wake Turbulence Re-Categorisation and Separation Minima on Approach and Departure
RECAT-EU-PWS	European Wake Turbulence Categorisation and Separation Minima on Approach and Departure - Pairwise
REG	Regulatory
RF	Radio Frequency
RNAV	Area Navigation
ROCAT	Runway Occupancy Time CATEGORIES
ROT	Runway Occupancy Time
ROT-LWS	ROT- Leader type-Wise Spacing
RPG	Radiometer Physics GmbH
RSP	Required Surveillance Performance
RRSM	Reduced Runway Separation Minima
RSSM	Reduced Surveillance Separation Minimum
RSVA	Reduced Separation in the Vicinity of the Aerodrome
SAC	Safety Criteria
SAP	Safety Assessment Plan
SAR	Safety Assessment Report
SARP	Standard and Recommended Practices
SASAI	Separation and Spacing Advisory Indicators

Acronym	Definition
SCRATCOH	Scheme for Regulation of Air Traffic Controllers' Hours
SEAC	SESAR European Airports Consortium
SeAP	Security Assessment Plan
SESAR	Single European Sky ATM Research programme
SINTEF	Stiftelsen for INdustriell og TEknisk Forskning
SJU	SESAR Joint Undertaking
SME	Small and Medium Enterprise
SORT	Safely Optimised Runway Throughput
SPDS	Surveillance Display Processing System
SPR	Safety and Performance Requirements
STD	Standard
SUT	System Under Test
SWIM	System Wide Information Model
S-PWS	Static Pair-Wise Separation
S-PWS-A	Static Pair-Wise Separation for Arrival
TAD	Test And Development
TAS	True AirSpeed
TBS	Time-Based Separation
TC	Terminal Control
TDI	Target Distance Indicator
TEAM	Tactical Enhanced Arrival Mode
TLDT	Target LanDing Time
TMA	Terminal Manoeuvring Area
TRL	Technical Readiness Level
TS	Technical Specification
TSAT	Target Start-up Approval Time
TTG	Time To Gain
TTL	Target To Loose
TTOT	Target Take-Off Time
TWR	Tower
VCCS	Voice Communications and Control System

Acronym	Definition
VCR	Visual Control Room
VIS1/VIS2	Visibility levels
VLD	Very Large Demonstration
WG	Working Group
WP	Work Package
WSVBS	Wirbelschleppen-Vorhersage- und -Beobachtungssystem (German for WVWS)
WT	Wake Turbulence
WTC	Wake Turbulence Category
WVWS	Wake Vortex Warning System
ZRH	Zurich Airport

Table 2: List of acronyms

3 Very Large Demonstration (VLD) Scope

The scope of VLD3-W2-SORT is to demonstrate the benefits and feasibility of various SESAR 2020 solutions in an operational environment. The solutions which were demonstrated in VLD3-W2-SORT and which can be found in Section 3.2 below contributed primarily to the Essential Operational Changes (EOC) category of “high-performing airport operations”. This was done by safely optimising the runway throughput via various technologies which essentially allow aircraft to operate at shorter distances in a leader-follower aircraft pair. Three demonstrations were held that will be described separately.

3.1 Very Large Demonstration Purpose

The VLD exercises that were performed were of a different nature. One consisted of a Real Time Simulation, one of a Live trial with Shadow-mode technique and one consisted of development and pre-industrialisation activities towards a real physical product and installation.

In Work Package 02 (WP2), the use of aircraft type-specific pairwise separation will be used at Heathrow Airport, focusing on the management of Runway Occupancy Time (ROT) and the reduction of the Minimum Radar Separation (MRS), supported by a separation delivery tool for the ATC controller. Improved management of ROT will result in the separation indicators being placed closer together for some pairs, using pairwise ROT values, as well as enhancements that allow ROT to be tailored to the conditions. A reduction in the MRS will see aircraft spaced closer together depending on the other constraining factors e.g. met conditions and aircraft performance characteristics. This will enable a higher runway throughput, increasing the movement rate of the airport and reducing airborne holding.

The main demonstration purpose of the WP3 Solution is to show that a passive, robust and relatively inexpensive method to accelerate wake vortex decay in ground proximity can be considered a major breakthrough to increase flight safety and potential airport capacity. After reaching the VLD3 targets successfully, Vienna Airport and other major airports in Europe may install plate lines at the runway ends to avoid the encounters during final approach mostly leading to go-arounds. The installation of plate lines at a major airport would be the best way to promote and to spread the plate line concept.

The main demonstration purpose of the WP5 Solution is to show that capacity gain can be brought by use of an Integrated Runway Sequence Function, providing an optimised arrival and departure sequence with accurate TTOTs and TLDTs, including dynamic balancing of arrivals and departures on parallel runways in mixed mode and also balancing of arrivals and departures between the runways when one runway is used mainly for departures and one runway is used mainly for arrivals.

Together these demonstrations will collect evidence of the concept(s) within the overall time-based separation concept. As such, the proposed large-scale demo VLD3-W2-SORT closes the gap between the actual concept development and the deployment (or pre-industrialisation) phases by demonstrating the operational and technical readiness. And by doing so de-risking the later deployment phases of these four solutions, either in real life trials and/or shadow modes trials at major European airports, this will ensure trust in the SESAR results.

3.2 SESAR Solution(s) addressed by VLD

See below the Table 3 with the SESAR Solutions, Operational Improvements and Enablers that were addressed by the demonstrations in VLD3-W2-SORT.

The descriptions of the SESAR Solutions and OIs were extracted from SESAR EATMA Dataset DS23 Draft.

SESAR Solution ID and Title	SESAR Description	Solution	OI Steps ref. (coming from EATMA)	Enablers ref. (coming from EATMA)
PJ.02-01-01 Optimised Runway Delivery (ORD) on Final Approach	The ORD concept is a controller support tool designed to assist approach controllers in managing the effect of compression that occurs on short final from the lead aircraft crossing the deceleration fix. The ORD tool consists of an indicator on the final approach that displays to the ATCOs the spacing needs to be achieved between each aircraft pair prior to the Deceleration Fix (DF) in order to achieve the required separation / spacing at the separation delivery point (usually the runway threshold). The ORD tool helps to ensure the consistent and efficient management of the spacing compression that occurs from the lead aircraft crossing the deceleration fix. This in turn helps to ensure consistent and efficient separation delivery at the separation delivery point. The ORD tool is used to support the application of Distance Based and Time Based wake separation rules including the ICAO, RECAT-EU, PWS-A and WDS-A wake separation schemes.		AO-0328 Optimised Runway Delivery (ORD) on Final Approach	A/C-47(*) Onboard management of meteorological data from onboard sensor for sharing and use by MET service providers
				AERODROME-ATC-17 Airport ATC tool to Support Time-Based Separation in Final Approach
				AERODROME-ATC-55 (STD-094) Aerodrome ATC System to support Optimised Runway Delivery on Final Approach based on Aircraft ROT categorisation
				AERODROME-ATC-68 (STD-093) Aerodrome ATC system to support optimised runway delivery on final approach
				APP ATC 99 ATC System to use Real-Time Meteo Information Received from Met Systems
				APP ATC 120 (STD-093) Approach ATC system to support optimised runway delivery on final approach

SESAR Solution ID and Title	SESAR Description	Solution	OI Steps ref. (coming from EATMA)	Enablers ref. (coming from EATMA)
	The solution targets capacity constrained runways during high intensity runway operations and applies to very large, large and possibly medium airports. As the ORD tool improves consistency and efficiency of separation delivery at the separation delivery point it will provide benefits in terms of human performance and safety. Benefits in terms of runway throughput capacity can also be gained during peak traffic periods in those airport that are capacity constrained.			APP ATC 156 ATC System to Support Time-Based Separation in Final Approach APP ATC 169 (STD-094) Approach ATC System to support Optimised Runway Delivery on Approach based on Aircraft ROT categorisation SWIM-APS-07a (*) Stakeholder systems consumption of G/G Meteorological Information services
PJ.02-01-04 Wake Turbulence Separations (for Arrivals) based on Static Aircraft Characteristics	Static PairWise Separation for arrivals (S-PWS-A) is the efficient aircraft type pairwise wake separation rules for final approach consisting of both the 96 x 96 aircraft type based wake separation minima (for the most common aircraft in ECAC area) and the twenty wake category (20-CAT) based wake separation minima for arrival pairs involving all the remaining aircraft types.	AO-0306 Static Pairwise Separations (S-PWS) for Arrivals		AERODROME-ATC-42a (REG-0523) Airport ATC tool to support static pair-wise wake separation (S-PWS) in final approach APP ATC 118 (REG-0523) ATC System to support static pair-wise wake separation (S-PWS) on approach REG-0523 Regulatory provisions (AMC) for static pair-wise wake separation minima (S-PWS)
PJ.02-01-07 Wake Decay Enhancing Devices	PJ.02-01-07 is a technological solution reducing the Wake Turbulence Risk via positioning of decay enhancing devices that	POI-0037-AO / AO-0325¹ Reduction of wake turbulence risk considering acceleration of wake vortex decay		AIRPORT-08 Decay Enhancing Devices

¹ Inside DS23 the enabler AIRPORT-08 is no longer coupled to AO-0325 (as was the case in DS19), but it has been linked to POI-0037-AO

SESAR Solution ID and Title	SESAR Description	Solution	OI Steps (coming from EATMA)	ref. (coming from EATMA)	Enablers ref. (coming from EATMA)
	accelerate the Wake Vortex Decay in Ground Proximity.		in ground proximity/		
PJ.02-03 Minimum-Pair separations based on Required Surveillance Performance (RSP)	Minimum Pair Separations based on Required Surveillance Performance (RSP) aims the application (by ATC) of non-wake turbulence pair wise separation (PWS) of 2NM for arrivals on final approach based upon Required Surveillance Performance (RSP).		AO-0309 Minimum Radar Separations based upon Required Surveillance Performance (RSP)		APP ATC 120 Approach ATC System to support Optimised Runway Delivery on Final Approach APP ATC 159 Approach ATC system updated for Minimum Separation Based on Required Surveillance Performance (separation delivery) CTE-S01 Secondary SUR Radars CTE-S01a SSR Mode A/C/S CTE-S02 Primary SUR sensor CTE-S02a Primary Surveillance Radar METEO-03 Provision and monitoring of real-time airport weather information (PCP) METEO-04b Generate and provide MET information services relevant for Airport and final approach related operations (PCP) PRO-257 ATC Procedure to apply spacing minimum down to 2 NM REG-0526 Regulatory provisions for Minimum-Pair separations based on RSP (Required Surveillance Performance) A/C-48a Air broadcast of aircraft position/vector (ADS-B OUT) compliant with DO260B AERODROME-ATC-59 Enhanced Surveillance data processing on Airport Surface (APT) CTE-S04a Wide Area Multilateration (WAM)
PJ.02-08-01 Integrated Runway Sequence for full traffic	Optimised integration of arrival and departure traffic flows, for single and multiple runway airports with the use of a trajectory		TS-0301 Integrated Arrival Departure Management for full traffic		AERODROME-ATC-09c Improvement of operational orchestration among arrival / departure management and surface management services.

SESAR Solution ID and Title	SESAR Description	Solution	OI Steps (coming from EATMA)	ref. (coming from EATMA)	Enablers (coming from EATMA)
Optimization on Single and Multiple Runway Airports	based Integrated Runway Sequence.		optimisation on the runway		(Design of enhanced algorithm to balance arrival and departure flights in live traffic situations.) AERODROME-ATC-33 Coupled sequencing tool enhanced to better handle arrivals and departures. (Enhanced DMAN with integrated arrivals for efficient planning of runway sequences including probe functionality.) AERODROME-ATC-58 Agile synchronisation of arrivals with departure information for the same airport. (Enhanced DMAN with integrated arrivals for efficient planning of runway sequences including probe functionality.) SWIM-APS-12a Provision and Consumption of general information for air traffic management using SWIM (Will not be addressed inside the demonstration) APP ATC 164 APP ATC System adapted to support integrated arrival/departure sequence functionalities in ATCO's HMI. (Demonstrate new approach label functionality.)
PJ.02-08-02 Optimised use of runway configuration for multiple runway airports	The controller of a multiple runway airport is provided with decision support tools enhanced to allow runway configuration optimization and demand distribution refinement from planning phase throughout the day of operations, improving runway throughput, predictability and		TS-0313 Optimized Use of Runway Configuration for Multiple Runway Airports		AERODROME-ATC-74 (REG-HNA-18) (REG-HNA-19) Runway Demand and Capacity system enhanced for multiple runway airport working in Tactical and pre-Tactical timeframe. (Enhanced DMAN with integrated arrivals for efficient planning of runway sequences including probe functionality.)

SESAR Solution ID and Title	SESAR Description	Solution	OI Steps ref. (coming from EATMA)	Enablers ref. (coming from EATMA)
	punctuality on airport operations.			SWIM-APS-12a Provision and Consumption of general information for air traffic management using SWIM (Will not be addressed inside the demonstration)
				APP ATC 164 APP ATC System adapted to support integrated arrival/departure sequence functionalities in ATCO's HMI.
PJ.02-08-03 Reduced separation based on local Runway Occupancy Time (ROT) characterisation	The solution proposes to enhance runway throughput by enabling minimum distance-based surveillance separation reduction between some aircraft, based on the Runway Occupancy Time (ROT) characterisation of the leader aircraft. The operational application can be either based per aircraft type or per aircraft ROT-based category (ROCAT).	AO-0337 Reduced separation based on local Runway Occupancy Time characterization		AERODROME-ATC-55 (STD-094) Aerodrome ATC System to support Optimised Runway Delivery on Final Approach based on Aircraft ROT Characterisation.
				APP ATC 169 (STD-094) Approach ATC System to support Optimised Runway Delivery on Approach based on Aircraft ROT Characterisation

Table 3: SESAR Solution(s) under Demonstration

Note: (*) The enabler is no longer applicable in Dataset 23 Draft.

3.2.1 Deviations with respect to the SESAR Solution(s) definition

The WP2 and WP3 demonstrations will not use any departure elements of the solutions, nor will it address the use of single runway airports for mixed mode operations.

3.3 Summary of Demonstration Plan

The VLD3-W2-SORT project covers three demonstrations, of which one was a Real Time Simulation, one a Live trial with Shadow-mode technique and one a pre-industrialization set of activities.

Table 4 below provides an overview.

Work Package (WP)	Solution to be validated	Exercise ID	Description	OI's to be validated in exercise
WP2	PJ.02-01-01	EXE-VLD-03-001C	Optimised wake separation for arrivals with reduced MRS and enhanced ROT – pre-deployment Real-Time Simulation (RTS) for Heathrow Airport.	AO-0306 AO-0309 AO-0328 AO-0337
	PJ.02-01-04			
	PJ.02-03			
	PJ.02-08-03			
WP3	PJ.02-01-07	EXE-VLD-03-002	Wake decay enhancing concepts at Vienna Airport.	POI-0037-AO / AO-0325 ² with enabler AIRPORT-08 Decay Enhancing Devices
WP5	PJ02-08-01	EXE-VLD-03-004	Integrated Arrival Departure Management for Full Traffic Optimisation on the Runway	TS-0301
	PJ02-08-02	EXE-VLD-03-004	Optimized Use of Runway Capacity for Multiple Runway	TS-0313

Table 4: Summary of Demonstrations

3.3.1 WP2 - Optimised wake separation for arrivals with reduced MRS and enhanced ROT Exercise - EXE-VLD-03-001C

3.3.1.1 Demonstration Plan Purpose

The expected rapid growth in air traffic will lead to an increasing number of capacity-constrained airports. Therefore, airports have to significantly improve the runway and airport throughput whilst maintaining or increasing runway safety levels.

The use of time-based and aircraft type-specific pairwise separations will be used at Heathrow Airport, focusing on the management of Runway Occupancy Time (ROT) and the reduction of the Minimum Radar Separation (MRS), supported by a separation delivery tool for the ATC controller. Improved management of ROT will result in the separation indicators being placed closer together for some aircraft pairs, using pairwise ROT values, as well as enhancements that allow ROT to be tailored to the conditions. A reduction in the MRS will see aircraft move spaced together depending on the other constraining factors e.g. met conditions and aircraft performance. This will enable a higher runway throughput, increasing the movement rate of the airport and reducing airborne holding.

² Inside DS23 the enabler AIRPORT-08 is no longer coupled to AO-0325 (as was the case in DS19), but it has been linked to POI-0037-AO

The Pairwise system also provides an early indication of the required separation or spacing, which is displayed in Early Line Zero (ELZ) on the aircraft track data block on the radar display.

3.3.1.2 Operating method description

The RTS exercise described here for WP02/04 will use elements of Solutions PJ.02-01-01, PJ.02-01-04, PJ.02-03 and PJ.02-08-03 and will include solution #64 (Time Based Separation, TBS) as a baseline. RSSM effects, or reduced MRS effects originally planned to be demonstrated in EXE-VLD-03-003 (see the DEMOP [41]) will be included in the WP2 exercise.

The elements of PJ.02-01 used are Wake Turbulence Separations (for Arrivals) based on Static Aircraft Characteristics (PJ.02-01-04) and Optimised Runway Delivery (ORD) on Final Approach (PJ.02-01-01). These solution elements will be used to implement the baseline Pairwise Time-Based Separation with Optimised Runway Delivery.

The element of PJ.02-03 used relates to MRS based upon Required Surveillance Performance (RSP). This solution element is incorporated to enable the reduction of the MRS within the Pairwise based platform allowing closer positioning of aircraft on final approach.

The element of PJ.02-08-03 used relates to the improved management of Arrival Runway Occupancy Time (AROT). This will also be used within the wider Pairwise Time-Based Separation environment to better predict the time taken on the runway for all aircraft, enhancing efficiency. The Runway Occupancy Time predictions are derived from NATS internal research and are specific to the Heathrow Airport operation. Additionally, there are considerations made for the Airline and Aircraft Type based on behaviour seen historically at Heathrow Airport. As part of the solution, the concept also contains mechanisms for managing larger ROT constraints required in non-standard conditions, such as in the event of a runway exit closure.

For exercise EXE-VLD-03-001C, the pre-deployment RTS, Approach Controllers will take part in multiple exercises using the Intelligent Approach Pairwise solution, with the intent of demonstrating the feasibility of the combined solution and benefits over using the current operational version of eTBS, which uses RECAT-EU Wake Turbulence Categorisation.

Approach Controllers will vector aircraft from the holding stacks, updating the order and information for their electronic flight progress strips in line with their intended approach sequence. The Pairwise system provides an early indication of the required separation or spacing which is displayed as Early Line Zero (ELZ) on the aircraft track data block on the radar display. As the aircraft approaches the extended runway centreline, an indicator will be generated based on the largest constraint between each aircraft pair (Wake, Spacing or Runway Occupancy Time) and with ORD distance incorporated. The Approach Controller will position the aircraft on the indicators and monitor their progress on final approach to the point where control would be transferred to the Tower.

Tower Controllers were present to observe an emulated tower radar display with the tower indicator presentation for feedback but did not have an active role in the simulation.

3.3.1.3 Summary of Demonstration Objectives and success criteria

Demonstration Objective	Demonstration Success criteria	Coverage and comments on the coverage of Demonstration objectives	Demonstration Exercise Objectives	Demonstration Exercise Success criteria
OBJ-VLD-03-001C-ACC	CRT-VLD-03-001C-ACC-001	Full Coverage	EXE-OBJ-VLD-03-001C-ACC To assess the acceptability of reduced MRS and PWS TBS	EXE-CRT-VLD-03-001C-ACC-001 The combined solution is found to be acceptable to controllers under all runway operating configurations demonstrated
	CRT-VLD-03-001C-ACC-002			EXE-CRT-VLD-03-001C-ACC-002 The combined solution is found to be acceptable to controllers under all wind conditions demonstrated
	CRT-VLD-03-001C-ACC-003			EXE-CRT-VLD-03-001C-ACC-003 The combined solution is found to be acceptable to controllers when managing aircraft pairs with ROT or Spacing as the maximum constraint
	CRT-VLD-03-001C-ACC-004			EXE-CRT-VLD-03-001C-ACC-004 The combined solution is found to be acceptable to controllers when managing aircraft pairs with Wake as the maximum constraint
	CRT-VLD-03-001C-ACC-005			EXE-CRT-VLD-03-001C-ACC-005 The combined solution is found to be acceptable to controllers when managing scenarios where a wake breakthrough indicator is present
	CRT-VLD-03-001C-ACC-006			EXE-CRT-VLD-03-001C-ACC-006 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing LVPs (Low Visibility Procedures)
	CRT-VLD-03-001C-ACC-007			EXE-CRT-VLD-03-001C-ACC-007 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing VIS2 (Visibility Condition 2)
	CRT-VLD-03-001C-ACC-008			EXE-CRT-VLD-03-001C-ACC-008 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing runway inspections
	CRT-VLD-03-001C-ACC-009			EXE-CRT-VLD-03-001C-ACC-009 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing EMT (Early Morning TEAM)
	CRT-VLD-03-001C-ACC-010			EXE-CRT-VLD-03-001C-ACC-010 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing departure gaps during EMT

	CRT-VLD-03-001C-ACC-011			EXE-CRT-VLD-03-001C-ACC-011 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing tactical spacing gaps
	CRT-VLD-03-001C-ACC-012			EXE-CRT-VLD-03-001C-ACC-012 The combined solution is found to be acceptable to controllers in missed or broken off approach scenarios
	CRT-VLD-03-001C-ACC-013			EXE-CRT-VLD-03-001C-ACC-013 The combined solution is found to be acceptable to controllers in aircraft speed non-conformance scenarios
	CRT-VLD-03-001C-ACC-014			EXE-CRT-VLD-03-001C-ACC-014 The combined solution is found to be acceptable to controllers in missing aircraft wake category information scenarios
	CRT-VLD-03-001C-ACC-015			EXE-CRT-VLD-03-001C-ACC-015 The generation and display of the Early Line Zero to support the Base Leg turn is found to be acceptable to controllers
OBJ-VLD-03-001C-EFF	CRT-VLD-03-001C-EFF-001	Full Coverage	EXE-OBJ-VLD-03-001C-EFF To assess the impact of reduced MRS and PWS TBS on operational efficiency	EXE-CRT-VLD-03-001C-EFF-001 The average arrival movement rate increases when compared to the reference scenario
	CRT-VLD-03-001C-EFF-002			EXE-CRT-VLD-03-001C-EFF-002 The number of aircraft pairs that have minimum radar separation as their maximum constraint decreases when compared to the reference scenario
	CRT-VLD-03-001C-EFF-003			EXE-CRT-VLD-03-001C-EFF-003 The effectiveness of the delivery of aircraft to the separation minima at the base leg stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-004			EXE-CRT-VLD-03-001C-EFF-004 The effectiveness of the delivery of aircraft to the separation minima at the intercept stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-005			EXE-CRT-VLD-03-001C-EFF-005 The effectiveness of the delivery of aircraft to the separation minima at the final approach stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-006			EXE-CRT-VLD-03-001C-EFF-006 The delivery conformance to the displayed indicators on the final approach is shown to be acceptable
OBJ-VLD-03-001C-ENV	CRT-VLD-03-001C-ENV-001	Full Coverage	EXE-OBJ-VLD-03-001C-ENV To assess the impact of reduced MRS and PWS TBS on environmental efficiency	EXE-CRT-VLD-03-001C-ENV-001 Average CO2 emissions per flight are reduced when compared to the reference scenario

OBJ-VLD-03-001C-HP	CRT-VLD-03-001C-HP-001	Full Coverage	EXE-OBJ-VLD-03-001C-HP	EXE-CRT-VLD-03-001C-HP-001 Controller workload is shown to remain within acceptable levels
	CRT-VLD-03-001C-HP-002			EXE-CRT-VLD-03-001C-HP-002 To assess the impact of reduced MRS and PWS TBS on human performance
	CRT-VLD-03-001C-HP-003			EXE-CRT-VLD-03-001C-HP-003 Situational Awareness is shown to remain at the same level or is improved
	CRT-VLD-03-001C-HP-004			EXE-CRT-VLD-03-001C-HP-004 The likelihood and consequence of human error are assessed as remaining within acceptable levels
	CRT-VLD-03-001C-HP-005			EXE-CRT-VLD-03-001C-HP-005 The procedures are found to be acceptable by controllers
	CRT-VLD-03-001C-HP-006			EXE-CRT-VLD-03-001C-HP-006 The Method of Operations are found to be acceptable by controllers
	CRT-VLD-03-001C-HP-007			EXE-CRT-VLD-03-001C-HP-007 The teamwork and communication enabled are shown to be acceptable
	CRT-VLD-03-001C-HP-008			EXE-CRT-VLD-03-001C-HP-008 User roles and responsibilities are shown to remain acceptable
	CRT-VLD-03-001C-HP-009			EXE-CRT-VLD-03-001C-HP-009 User Confidence is shown to remain within acceptable limits
	CRT-VLD-03-001C-HP-010			EXE-CRT-VLD-03-001C-HP-010 The tool is shown to support the controllers in their decision making processes
OBJ-VLD-03-001C-SAF	CRT-VLD-03-001C-SAF-001	Full Coverage	EXE-OBJ-VLD-03-001C-SAF	EXE-CRT-VLD-03-001C-SAF-001 Controller trust in the integrity of the tool support and reliance on indicators are shown to be acceptable
	CRT-VLD-03-001C-SAF-002			EXE-CRT-VLD-03-001C-SAF-002 The number of missed approaches due to insufficient spacing is no greater than in currently operations
	CRT-VLD-03-001C-SAF-003			EXE-CRT-VLD-03-001C-SAF-003 To assess the impact of reduced MRS and PWS TBS on interoperability evidence can be produced to confirm that the elements of all solutions when combined do not degrade the level of safety.
	CRT-VLD-03-001C-SAF-004			EXE-CRT-VLD-03-001C-SAF-004 The combined solution and procedures cause no losses of separation in the demonstration exercise
OBJ-VLD-03-001C-SEC	CRT-VLD-03-001C-SEC-001	Full Coverage	EXE-OBJ-VLD-03-001C-SEC	EXE-CRT-VLD-03-001C-SEC-001 The combined solution and procedures cause no increase in the frequency of go arounds when compared to the reference scenario A Security Risk Assessment is carried out

CRT-VLD-03-001C-SEC-002	To assess the impact of reduced MRS and PWS TBS on operational security	EXE-CRT-VLD-03-001C-SEC-002	Security Risk Treatments are applied
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Table 5: Summary of Demonstration Objectives and success criteria (EXE-VLD3-001C)

3.3.1.4 Demonstration Assumptions

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-001C-001	2NM Minimum Radar Separation Approval	Regulatory	It is assumed that the approval of the 2NM MRS with the national regulator at a point after the demonstration does not necessitate any change to procedures from those demonstrated in the exercises.	The operational assurance for live operations has not been confirmed at the point of the demonstration.	None
ASS-VLD-03-001C-002	National Lockdowns	Time planning	It is assumed that there will be no further national lockdowns that may impact the ability of NATS to hold the demonstration activities.	Due to the impact of COVID and lockdowns, activity on operational sites was historically restricted.	A National Lockdown may restrict the ability for individuals to attend the facility and for rostering Controllers.
ASS-VLD-03-001C-003	Applicability to Other Airports	Applicability of research results	It is assumed that the results from Heathrow Approach will be applicable to other airports of equivalent size and throughput.	The ROT characteristics and development have specifically focussed on Heathrow Airport which is the first operational deployment of the combined solution.	None

Table 6: Demonstration Exercise Assumptions (EXE-VLD3-001C)

3.3.1.5 Demonstration Exercises List

Development simulations took place in late 2021 and in 2022. These activities were limited due to the Pre-FAT nature of the software build. The demonstration exercise was conducted in Q1 2023.

3.3.1.5.1 EXE-VLD3-001C

[EXE]

Identifier	EXE-VLD-03-001C
Title	Real-Time Simulation
Description	Demonstrate the feasibility and benefits of implementing Pairwise TBS, reduced MRS and improved ROT management in an RTS pre-deployment trial for London Terminal Control Centre.
Demonstration Technique	Real Time Simulation
KPA/TA Addressed	Human Performance, Operational Feasibility, Safety, Security, Performance and Acceptability
Number of flights	Minimum 250
Start Date	10/02/2023
End Date	28/03/2023
Demonstration Coordinator	NATS
Demonstration Platform	IA, ExCDS, NODE, VCCS
Demonstration Location	NATS London Terminal Simulator
Status	Closed
Dependencies	None

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	SESAR Solution PJ.02-01
<SESAR Solution>	SESAR Solution PJ.02-03
<SESAR Solution>	SESAR Solution PJ.02-08
<Demo Objective>	Demo Objective Identifier (DEMOP) OBJ-VLD-03-001C-ACC OBJ-VLD-03-001C-EFF

	OBJ-VLD-03-001C-ENV
	OBJ-VLD-03-001C-HP
	OBJ-VLD-03-001C-SAF
	OBJ-VLD-03-001C-SEC

Table 7: Demonstration Exercise EXE-VLD-03-001C layout

3.3.2 WP3 - Wake decay plate lines - Exercise - EXE-VLD3-002

3.3.2.1 Demonstration Plan Purpose

The objective of this ‘demonstration’, actually a development and pre-industrialisation task, is to industrialize the plate line concept into a prototype of the plate and its installation, which is suitable for permanent deployment and ready for approval by authorities.

3.3.2.2 Operating method description

Operating methods are not influenced by the wake decay concept solution as it constitutes a passive system, see PJ02-01 OSED [3].

However the VLD3 ‘exercise’ was structured by the following activities:

1. Elaborate a technical plate line design as well as the design for its installation for permanent deployment at an airport
2. Prepare all material for authority approval like expert opinions on statics etc. needed to receive the approval from the authorities for the installation of plate lines at an airport location
3. Installation of the plate prototype in a suitable environment, e.g. at Vienna airport considering legal, and stakeholders’ requirements
4. Thorough quantification of the acceleration of wake vortex decay by plate lines based on the validation results stemming from WAVE-1
5. Assessment of achievable reductions of separation minima
6. Conducting a demonstration/visitor’s day in order to demonstrate that all required qualifications for the installation of plate lines at airports have been fulfilled within VLD3

Related to the above defined data analysis tasks 4 and 5, the primary focus was on **reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines** and on the **Assessment of achievable reductions of separation minima**.

This resulted in essentially a safety analysis outcome with expectations for airport capacity impact.

It is noted that the analysis has been based on a measurement campaign that has been accomplished from 6 May 2019 until 28 November 2019 at Vienna International Airport in the SESAR Joint Undertaking “Increased Runway and Airport Throughput” project (PJ.02 EARTH). Detailed results can be found in Appendix B.

3.3.2.3 Summary of Demonstration Objectives and success criteria

This exercise only had one demonstration objective, i.e. OBJ-VLD-03-002-001, see DEMOP [5], sections 4.4 and 5.3.3 and the table below. The method developed for RECAT-EU and even RECAT-EU-PWS was successfully applied. This implicitly implied that:

- Statistical significant results were demonstrated.
- All tasks as defined under section 3.3.2.2 have been satisfactorily concluded.

The Summary of Demonstration Objectives and success criteria of this exercise can be found in the Table 8 below

[OBJ]	Exercise	Identifier	Demonstration Exercise Objectives	Demonstration Success Id	Demonstration Exercise Success criteria
OBJ2	EXE-VLD-03-002	OBJ-VLD-03-002-001	reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines for different environmental conditions and aircraft types achievable reductions of separation minima	CRT-VLD-03-002-001	Method developed for RECAT-EU has been successfully applied

Table 8: Summary of Demonstration Objectives and success criteria (EXE-VLD3-002)

3.3.2.4 Demonstration Assumptions

It is assumed that the overall scenario at runway 16 of Vienna airport is representative for other runway situations at major airports. This assumption appears appropriate because wake vortex behaviour in ground proximity is controlled by aircraft types, surface roughness and wind conditions which are similar for other airports.

Further, it is assumed that the measurement statistics suffice for robust assessment of the qualification of the plate lines to accelerate wake vortex decay. It is also assumed that the measurement results are suitable to follow the rationale developed for RECAT-EU and RECAT2-EU with respect to the wake vortex generation altitude, the analysed aircraft types and the amount of the processed wake vortex evolutions measured by lidar. These assumptions appear justified because measurement days with reasonable worst-case conditions were chosen such that a comprehensive data base (more than 1200

vortex pair evolutions) of long-lived vortices could be established which has been processed with good quality.

The assumptions have been detailed in the Table 9 below.

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-002-001	representativity	representativity	overall scenario at Vienna airport is considered representative for other major airports	wake vortex behaviour in ground proximity is controlled by aircraft types, surface roughness and wind conditions which are similar for other airports	medium
ASS-VLD-03-002-002	Statistical significance	Statistical significance	data suffices for robust assessment of qualification of plate lines to accelerate wake vortex decay	more than 1200 vortex pair evolutions were carefully chosen from the data base and processed with high quality	high
ASS-VLD-03-002-003	Statistical significance	Statistical significance	measurement results are suitable to follow the rationale developed for RECAT-EU	reasonable worst-case conditions were chosen such that long-lived vortices were collected which were processed with high quality	medium

Table 9: Demonstration Assumptions overview

3.3.2.5 Demonstration Exercises List

3.3.2.5.1 EXE-VLD-03-002

The exercise details have been detailed in the Table 10 below.

[EXE]

Identifier	EXE-VLD-03-002
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Title	Wake decay enhancing devices
Description	Demonstrate the safety gains and potential capacity gains that can be achieved by the installation of plate lines and establish an authority approved prototype of a plate design for permanent installation at airports.
Demonstration Technique	Design and installation of plate prototype and analysis of measurement data collected in wave 1.
KPA/TA Addressed	Safety, capacity, fuel efficiency, resilience
Number of flights	~ 10,000 approaches measured, over 1,000 wake evolutions to be analysed
Start Date	01/04/2020
End Date	30/06/2023
Demonstration Coordinator	DLR
Demonstration Platform	Single Plate installations
Demonstration Locations	1) At Rauchenwarth (near Vienna Airport) 2) At DLR Oberpfaffenhofen (on site)
Status	1) Achieved and Closed at Feb 2023 2) Ongoing at Oberpfaffenhofen (closure expected before end of June'23)
Dependencies	None

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	SESAR Solution PJ.02-01
<Demo Objective>	OBJ-VLD-03-002-001

Table 10: Demonstration Exercise EXE-VLD-03-002 layout

3.3.3 WP5 - Integrated Runway Sequencer Function Exercise (EXE-VLD-03-004)

3.3.3.1 Demonstration Plan Purpose

The purpose of the WP5 exercise was to demonstrate that capacity gain can be brought by use of an Integrated Runway Sequence Function, providing an optimised arrival and departure sequence with accurate TTOTs and TLDTs, including dynamic balancing of arrivals and departures on parallel runways in mixed mode and also balancing of arrivals and departures between the runways when one runway is used mainly for departures and one runway is used mainly for arrivals. the benefits of integrated TMA and runway throughput solutions.

3.3.3.2 Operating method description

This WP5 – Integrated Runway Sequencer Function exercise was a live trial demonstration with shadow-mode technique of Integrated Arrival Departure Management.

Demonstration in shadow mode with live traffic the operational concept, benefits and issues associated with the use of an Integrated Runway Sequence Function at Stockholm Arlanda were assessed.

The Integrated Runway Sequence function was demonstrated in mixed-mode operations on two parallel runways to optimise the combined sequence of arrival and departure flights for each runway and also balance the number of flights between the runways. The tool was also demonstrated on runway configurations that are frequently used in today's operations.

It covers the OI step TS-0301 and TS-0313.

OI Step code	OI Step title	OI Step coverage
TS-0301 (PJ.02-08-01)	Integrated Arrival Departure Management for Full Traffic Optimisation on the Runway	Full
A full integration of arrival and departure management processes provides dynamic assistance to the Tower controllers to optimize runway throughput. Additionally, to runway throughput optimization, making best use of variable taxi time, minimum separations and runway occupancy time could optimize arrival/departure spacing.		

OI Step code	OI Step title	OI Step coverage
TS-0313 (PJ.02-08-02)	Optimized Use of Runway Capacity for Multiple Runway	Full
The controller of a multiple runway airport is provided with decision support tools enhanced to allow runway capacity optimization from planning phase throughout the day of operation, improving predictability on airport operations		

The integrated runway sequence function (IRSF) was demonstrated in the VLD in shadow-mode using live traffic as well as with recorded material. In an operational scenario, the IRSF provided ATCOs with an optimized integrated arrival and departure runways sequence, and as such fulfilled the operational improvements TS-0301 and TS-0313, in particular when used in full capacity traffic and on multiple runways.

The use of an Integrated Runway Sequence Function (IRSF) was expected to bring the following benefits, even if not necessarily all at the same time, each operational situation requiring a trade-off between different KPIs:

- CAP KPA: Increase **RWY capacity** and **RWY throughput** by optimising the spacing between arrivals and departures in all situations in a dynamic way; and also, by balancing between the runways in parallel, mixed mode, when applicable.
- PRD KPA: Increase **predictability and punctuality** by making all ATS units follow a common plan based on an accurate integrated runway sequence;
- ENV KPA: Increase **fuel efficiency** and thereby reducing **CO2 emission** by **reducing overall flight duration** (mostly reducing the need for holdings and the overall taxi-time as a result of following an accurate integrated runway sequence). The Integrated Runway Sequence Function can also help to avoid **noise** sensitive areas by suggesting to move flights to another runway.

Recommendation from the V3 stage that has been considered in the VLD are as follows [2]:

- Tuning and local adaptation of the Integrated Runway Sequence Function algorithm:
 - Tuning/local adaptation of at what stage and in which situations the Integrated Runway Sequence Function can and cannot perform gap size updates. This is done by allowing the gap size ability to be on or off in the VLD setup.
 - Tuning/local adaptation of which actual events the algorithm should respond to. This will be listed and assessed during live demo (mainly A-CDM times).
 - Tuning/local adaptation of desired departure buffer at the runway hold (which also affects the departure taxi time). This will be further looked at with the help of new environmental setting with ability to adjust departure buffer.
 - Defined Airport and ATC prioritisation strategies in view of different objectives per KPA/KPI depending on the traffic and the time of the day.
- Tuning/local adaptation of how the system updates according to real events:
 - Investigate how the system updates according to real events, procedures for failure mode and recovery from failure mode and how the system is affected by the turn-around process.
 - Investigate in which situations it is better that the systems initiate automatic updates rather than by ATCO manual input; for example, it might be better that ground radar and/or TWR e-strip updates the sequence according to the real situation on taxi ways rather than that the ATCOs performing a manual input. This will be further looked at with system setting including “manual, semi-automatic and automatic” option.

- Valuable suggestions for further improvements to the HMI have been gathered in the V3 phase and they will be used for further research/implementation with feedback from ATCOs during demonstration.
 - Tuning/local adaption of the HMI.
- Investigate the effect of the turn-around process (with more TOBTs being missed, conflicts on taxi ways etc.) This will be further looked at during demonstration.
- Investigate the possibility to combine the concept with spacing advisories (either in distance or time) by use of chevrons (defined for Time based separation).
- With results from V3-phase this concept is mature and procedures/systems will be further refined with the live trials by use of shadow mode technique. The objective is to enhance the local adaptation with involvement of Airport Operator, Airspace Users and ATC at Stockholm-Arlanda by demonstrations:
 - The experiences from V3 validation with use of parallel runways. VLD was done in live traffic with parallel runways in segregated mode.
 - System support to ensure predictability and high-capacity levels (with additional capability to during arrival traffic peaks manage around 50 flights per hours and during departure peaks to manage around 50 flights per hour). This includes landing five arrivals on runway mainly dedicated for departures, this is in line with new environmental permit for the Stockholm-Arlanda.
 - New STAR design used for parallel runways. This is done by close coordination with LFV SWEA project for new airspace and use of short RNP-AR approached for 19R and 01L.

Figure 1 illustrates the processes and events linked to the management of the Integrated Runway Sequence.

- **Arrival traffic information** is described above the timeline with Top of descent, Time to lose and Time to gain and finally the Target Landing Time.
- **Departure traffic information** is described below the timeline with push back (including start-up) and taxi out time to the runway (EXOT).
- **Business Trajectory** describing the progress of Scheduled and Reference Business Trajectory (RBT) with final update by Airspace Users revised RBT.

One hour before estimated arrival/departure time, the Integrated Runway Sequence function provides an integrated runway sequence with setting of Target landing times and Target take-off times. In a certain time horizon before estimated arrival/departure time there will be an update of departure sequence and a fine tuning of arrival spacing values resulting in the update of Target landing times and Target take-off times. At this time, the sequence order is fixed in the integrated runway sequence.

Depending on options for deployment, these processes and events linked to the management of the Integrated Runway Sequence can be supported partly by AMAN and/or DMAN. The integrated runway

sequence is either built on its own or complements the arrival sequence built by AMAN and/or the departure sequence built by DMAN.

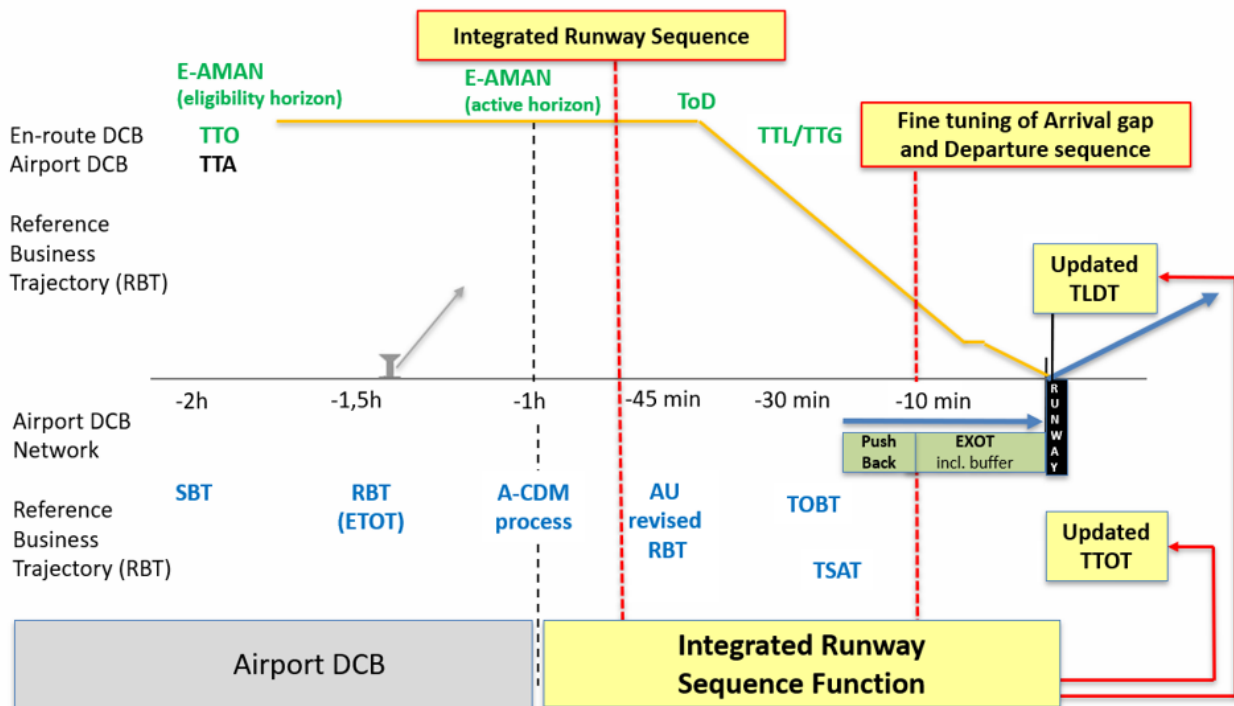


Figure 1: Integrated RWY Sequence Function (IRSF)

The demonstration is a shadow-mode trial with live traffic taking place in demonstration rooms in both Stockholm ATCC buildings and at Malmö Sturup as well as a pre-recorded trial taking place in Swedavia tower building Stockholm-Arlanda. The demonstration platform consists of the LFV-COOPANS AVVIP simulator, the Integrated Runway Sequence Function provided by SINTEF and an enhanced DMAN provided by Swedavia and further developed for the shadow-mode trial by LFV, including calculation and display of both arrivals and departures.

The Integrated Runway Sequence Function will set the proposed integrated sequence and communicate information about the sequence to the AAVIP simulator and the DMAN.

The DMAN will provide the presentation of the integrated arrival/departure (ARR/DEP) runway sequence(s), including balancing of flights between the parallel runways. The TWR and ATCC Supervisors will coordinate and interact with the DMAN HMI to set runway in use, probe the most optimal runway configuration and closure of runways when needed.

The APP label HMI in the shadow-mode system will be updated and evaluated. In this shadow-mode trial with live traffic the ATC operations will not be affected, therefore there will be no manual interactions with the executive working positions.

Today, operations work on segregated mode with one RWY for landing and one for departures. The solution will demonstrate the ability for predictability and flexibility, in this way arrivals can land on RWY mainly for departures and departures can depart on RWY mainly for landings.

3.3.3.3 Summary of Demonstration Objectives and success criteria

Demonstration in shadow mode with live traffic the operational concept, benefits and issues associated with the use of an Integrated Runway Sequence Function at Stockholm Arlanda.

The Integrated Runway Sequence function was demonstrated in mixed-mode operations on two parallel runways to optimise the combined sequence of arrival and departure flights for each runway and also balance the number of flights between the runways. The tool was also demonstrated on runway configurations that are frequently used in today's operations.

This exercise had five demonstration objectives, see DEMO Plan [5], sections 4.4. and 5.5.

The Summary of Demonstration Objectives and success criteria of this exercise can be found in the Table 11 below.

[OBJ]	Exercise	Identifier	Demonstration Exercise Objectives	Demonstration Success criteria Id	Demonstration Exercise Success criteria
OBJ4	EXE-VLD-03-004	OBJ-VLD-03-004-001	Capacity: To show potential for increased runway capacity, with at least 5%, with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-001	Potential for increased runway capacity with the introduction of the Integrated Runway Sequence Function has been demonstrated
	EXE-VLD-03-004	OBJ-VLD-03-004-002	Environment: To show potential for decreased departure taxi time with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-002	Potential for decreased departure taxi time with the introduction of the Integrated Runway Sequence Function has been demonstrated
	EXE-VLD-03-004	OBJ-VLD-03-004-003	Environment: To show potential for decreased arrival flying time with the use of the Integrated Runway	CRT-VLD-03-004-003	Potential for decreased arrival flying time, in relation with capacity increase with the introduction of the Integrated Runway Sequence Function

[OBJ]	Exercise	Identifier	Demonstration Exercise Objectives	Demonstration Success criteria Id	Demonstration Exercise Success criteria
			Sequence Function		has been demonstrated
	EXE-VLD-03-004	OBJ-VLD-03-004-004	Environment: To show potential for avoiding noise sensitive area with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-004	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated
	EXE-VLD-03-004	OBJ-VLD-03-004-005	Predictability and Punctuality: To show potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function	CRT-VLD-03-004-005	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function has been demonstrated

Table 11: Summary of Demonstration Objectives and success criteria (EXE-VLD3-004)

3.3.3.4 Demonstration Assumptions

Various assumptions are made for: traffic level, traffic mix, traffic pattern, airspace layout, airport characteristics, ground tools/technology, aircraft performance, procedures, A-CDM, environmental constraints/characteristics, regulatory considerations.

The assumptions have been detailed in the Table 12 below.

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-004-001	Traffic level	Other airports	Overall scenario at Stockholm-Arlanda airport is considered representative for other major airports	Stockholm-Arlanda airport is seen as a major airport	High

Table 12: Demonstration Assumptions overview (EXE-VLD-03-004)

3.3.3.5 Demonstration Exercises List

3.3.3.5.1 EXE-VLD3-004

The exercise details have been detailed in the Table 13 below.

[EXE]

Identifier	EXE-VLD-03-004
Title	Integrated Runway Sequence Function
Description	Stockholm-Arlanda Airport and TMA environment with focus on Tower and Approach. The objective is to assess the impact when using Integrated Runway Sequence function for traffic optimisation on various runway configurations that are used in real operations as well as in parallel independent runway operations to show the potential of using these runway configurations. The VLD will demonstrate the benefits and implications of using the concept and proposed tool in the particular operational environment.
Demonstration Technique	Shadow mode operation with live traffic at Stockholm ATCC and at Malmö Sturup as well as recorded trial at Swedavia tower building.

KPA/TA Addressed	Capacity, Human Performance, Predictability and Punctuality, Safety and Environment
Number of flights	N/A
Start Date	07-03-2022
End Date	17-06-2022
Demonstration Coordinator	LFV
Demonstration Platform	AVVIP simulator, the Integrated Runway Sequence Function provided by SINTEF and Enhanced DMAN
Demonstration Location	Stockholm ATCC building, Malmö-Sturup and Swedavia tower building Stockholm-Arlanda.
Status	Closed
Dependencies	N/A

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	SESAR Solution PJ.02-01
<SESAR Solution>	SESAR Solution PJ.02-03
<SESAR Solution>	SESAR Solution PJ.02-08
<Demo Objective>	OBJ-VLD-03-004-001 OBJ-VLD-03-004-002 OBJ-VLD-03-004-003 OBJ-VLD-03-004-004 OBJ-VLD-03-004-005

Table 13: Demonstration Exercise EXE-VLD-03-004 layout

3.4 Deviations

3.4.1 Deviations with respect to the S3JU Project Handbook

No deviations with respect to the SJU Project Handbook have been identified.

3.4.2 Deviations with respect to the Demonstration Plan

Deviations with respect to the Demonstration Plan [5] have been below- indicated per exercise.

3.4.2.1 WP2 - EXE-VLD-03-001C

A number of deviations associated with the tool functionality and the experimental design were unavoidable due to unexpected issues and constraints. The details of these are provided in Section A.2.

3.4.2.2 WP3 – EXE-VLD-03-002

The original plan to receive the approval for the installation of a plate prototype at Vienna airport could not be achieved as the authorities (BMK, Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology) did not support the approval of the installation of a single plate in the vicinity of the runway, without the beneficial effects of reducing the lifetimes of wake vortices generated by landing aircraft. Alternatively, Austro Control considered the installation of a complete plate line, which however could not be realized due to the strongly reduced air traffic given the Covid pandemic. In order to largely achieve the original goals of WP3, Austro Control tried to convince the authorities to grant the approvability of a plate line installation (eight plates) at Vienna airport, without actually installing all 8 plates at the end of the runway. This adjusted approach would have facilitated the installation of a plate line once the traffic demand has sufficiently recovered. Unfortunately, the BMK also refused this solution path.

So, a mitigation plan (D3.1.02) has been established describing the impact on WP3 in terms of tasks, outcome, high-level objectives, timing, resources, effort and budget. The main deviations are that the wake decay platform was not installed at the airport but at the antenna test centre Rauchenwarth close to Vienna airport. Further, the full documentation needed for authority approval of the plate installation was compiled however without the authority approval itself. This explicitly includes the external expert opinion regarding the plate design which is basically requested by the BMK. Correspondingly, also Milestone MS5 “Approval of National Authorities received on WP3 platform use” could not be achieved.

Additionally, another prototype plate will be erected on DLR premises in Oberpfaffenhofen next to the Institute of Atmospheric Physics in March or April 2023. The plate prototype will not only serve as a demonstration model for interested stakeholders, but also demonstrate how resistant the design is with respect to weather influences and particularly heavy storms. Such a demonstration will likely help to convince airport decision makers to install plate lines in the future.

3.4.2.3 WP5 – Integrated Runway Sequence Function – EXE-VLD-03-004

Deviations from the initial DEMOP for WP5 is an extended number of days for demonstration of the system at Swedavia tower building in Stockholm-Arlanda. This due to a high interest in the solution, which lead to the need for an extended demonstration period. This is seen as a positive deviation and did not affect the demonstration or the demonstration plan negative in any way.

4 Demonstration Results

4.1 Summary of Demonstration Results

The summary of all three demonstration results is provided in the Table 14 below.

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
OBJ-VLD-03-001C-ACC	To assess the acceptability of reduced MRS and PWS TBS	CRT-VLD-03-001C-ACC-001	The combined solution is found to be acceptable to controllers under all runway operating configurations demonstrated	Qualitative survey responses demonstrate that the pairwise concept is highly acceptable to controllers regardless of the runway in use.	OK
		CRT-VLD-03-001C-ACC-002	The combined solution is found to be acceptable to controllers under all wind conditions demonstrated	Qualitative survey responses showed that the pairwise concept is acceptable across all wind conditions demonstrated.	OK
		CRT-VLD-03-001C-ACC-003	The combined solution is found to be acceptable to controllers when managing aircraft pairs with ROT or Spacing as the maximum constraint	Qualitative survey responses showed that the pairwise concept is acceptable for managing aircraft pairs with ROT or spacing as the maximum constraint.	OK
		CRT-VLD-03-001C-ACC-004	The combined solution is found to be acceptable to controllers when managing aircraft pairs with Wake as the maximum constraint	Qualitative survey responses showed that the pairwise concept is acceptable for managing aircraft pairs with Wake as the maximum constraint.	OK
		CRT-VLD-03-001C-ACC-005	The combined solution is found to be acceptable to controllers when managing scenarios where a wake	Acceptability of the Wake Breakthrough indicator was generally accepted, as five controllers strongly agreed that HMI and indicator support was acceptable. However, one	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
			breakthrough indicator is present	controller somewhat disagreed, arguing that 0.5NM can sometimes be insufficient for recovery and that 0.75NM could be more suitable. It should be noted that the Wake Breakthrough behaviour is the same in Pairwise as in eTBS today, however this is a value that is adaptable and therefore can be taken forward for consideration.	
		CRT-VLD-03-001C-ACC-006	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing LVPs (Low Visibility Procedures)	During the operational scenarios a transition from VIS1 to VIS2 to LVPs and reverting back again was simulated. During the debrief the controllers commented that they found the Indicator support to be acceptable. However, there were comments in the end of participation questionnaire that the information in the Status Spacing Window could stand out more and in addition, more exposure to these types of scenarios is required for familiarity of using the Spacing input functionality.	OK
		CRT-VLD-03-001C-ACC-007	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing VIS2 (Visibility Condition 2)	See above relating to CRT-VLD-03-001C-ACC-006.	OK
		CRT-VLD-03-001C-ACC-008	The indicator support, HMI and associated procedures are found to be acceptable to controllers when	During Runway inspections, it was noted that in the majority of cases, the lead aircraft will land before the follower has turned base leg and therefore the indicator and ELZ value will be lost. This was discussed during	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
			managing runway inspections	the debrief and all of the controllers felt this was not an issue, as they are able to remember the 4DME indicator value and 'round up', and if not, refer to the threshold value that is displayed on the designator. There was no concern regarding safety, due to the fact it is a spacing gap rather than a separation.	
		CRT-VLD-03-001C-ACC-009	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing EMT (Early Morning TEAM)	Dependant runway constrained aircraft showed high acceptability from controllers, but only three strongly agreed, while the other three rated this somewhat agree. One controller did not like the ELZ for dependent aircraft being displayed as '0.0'.	OK
		CRT-VLD-03-001C-ACC-010	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing departure gaps during EMT	Whilst the ability to input departure gaps into ExCDS during EMT was considered acceptable, there was feedback given on the HMI design of the Spacing Status Window Functionality. One controller Strongly disagreed that the display of 'TFN' to show that a global spacing policy is in force was acceptable and would prefer more of an attention getter (e.g., either by having this text in a different colour or by having a designator automatically generated). A change required to current procedures was highlighted in terms of the distance specified by Tower when requesting departure gaps. Today the Tower will ask for the distance that they require when the lead aircraft reaches 4DME. With the Pairwise concept, the Tower needs to	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
				request the gap relative to the runway threshold. During EMT with departure gaps in force, the controllers observed indicator constraints changing from a spacing to a dependent for some aircraft pairs when leader passes 1 DME. This is correct system behaviour and shall be covered in training to ensure the controllers understand this system behaviour.	
		CRT-VLD-03-001C-ACC-011	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing tactical spacing gaps	Five out of six controllers agreed that they were able to input, edit and remove individual spacings effectively. One controller response was neutral, but commented that they need more exposure to using this functionality. For another controller, although they find the spacing functionality acceptable, they comment that this will 'take some getting used to' as it is a new way of using ExCDS than in current operations.	OK
		CRT-VLD-03-001C-ACC-012	The combined solution is found to be acceptable to controllers in missed or broken off approach scenarios	A blocked runway scenario was assessed on the second scenario day of the simulation. Several aircraft were instructed to conduct missed approaches, with several being broken off the approach and then the remaining aircraft switched to the other runway. The scenario worked successfully, with the controllers being able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs and missed approaches.	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
		CRT-VLD-03-001C-ACC-013	The combined solution is found to be acceptable to controllers in aircraft speed non-conformance scenarios	During the operational scenario testing days of the simulation, several speed non-conformance scenarios were attempted. However, this was difficult to set up in a simulated environment. Despite this, the indicator procedures to adopt in an infringement scenario were deemed to be acceptable by all participants.	OK
		CRT-VLD-03-001C-ACC-014	The combined solution is found to be acceptable to controllers in missing aircraft wake category information scenarios	An aircraft without a wake vortex category was assessed during the simulation. The tool behaved as designed and did not generate an indicator for this aircraft. The controllers were able to apply the defined procedures which require extra spacing to be applied ahead of and behind the aircraft and found this to be acceptable.	OK
		CRT-VLD-03-001C-ACC-015	The generation and display of the Early Line Zero to support the Base Leg turn is found to be acceptable to controllers	Qualitative feedback from controllers around ELZ were generally very positive, with participants agreeing that Early Line Zero is acceptable. The ELZ is seen as a benefit to the operation and useful as information to support the controller in the base legs turns, therefore improving predictability.	OK
OBJ-VLD-03-001C-EFF	To assess the impact of reduced MRS and PWS TBS on operational efficiency	CRT-VLD-03-001C-EFF-001	The average arrival movement rate increases when compared to the reference scenario	A benefit to arrival throughput is seen under all wind conditions, although the difference under light and moderate wind is not large enough to be highly indicative.	OK
		CRT-VLD-03-001C-EFF-002	The number of aircraft pairs that have minimum radar separation as their maximum constraint decreases when	As the MRS constraint at threshold is reduced to 2NM as part of the Heathrow Pairwise concept, ROT becomes the maximum constraint for non-wake pairs in all but the high wind conditions, where wake separation minima are reduced	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
			compared to the reference scenario	to a greater extent. This prompts a sizeable reduction in the proportion of MRS pairs, when compared to the equivalent eTBS run.	
		CRT-VLD-03-001C-EFF-003	The effectiveness of the delivery of aircraft to the separation minima at the base leg stage is shown to be acceptable	As a means of assessing the acceptability of separation delivery to the minima, the recorded events of technical losses of MRS were investigated. Based on post-analysis, it has been determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution, as no technical losses of MRS were reported in the solution scenario.	OK
		CRT-VLD-03-001C-EFF-004	The effectiveness of the delivery of aircraft to the separation minima at the intercept stage is shown to be acceptable	See above relating to CRT-VLD-03-001C-EFF-003.	OK
		CRT-VLD-03-001C-EFF-005	The effectiveness of the delivery of aircraft to the separation minima at the final approach stage is shown to be acceptable	See above relating to CRT-VLD-03-001C-EFF-003.	OK
		CRT-VLD-03-001C-EFF-006	The delivery conformance to the displayed indicators on the final approach is shown to be acceptable	For the displayed indicators (which only support wake and certain ROT pairs under eTBS), the aircraft position conformance to these indicators on final approach were processed as a distribution, both at the 4DME and at 1DME points. These distributions demonstrate that the delivery conformance to the displayed indicators was acceptable but is influenced by individual controller differences.	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
OBJ-VLD-03-001C-ENV	To assess the impact of reduced MRS and PWS TBS on environmental efficiency	CRT-VLD-03-001C-ENV-001	Average CO ₂ emissions per flight are reduced when compared to the reference scenario	Fuel burn analysis indicates an average saving of 14.84kg per flight. Using the direct link between fuel burn and the amount of CO ₂ produced (3.15 times the mass of fuel burnt), this equates to an average CO ₂ saving of 46.73kg per flight.	N/A
OBJ-VLD-03-001C-HP	To assess the impact of reduced MRS and PWS TBS on human performance	CRT-VLD-03-001C-HP-001	Controller workload is shown to remain within acceptable levels	Generally speaking, controllers didn't feel like WL would change very much (although it was pointed out during debriefs that it is likely the FIN would take on more work than the INT and support from the GS and INT would be preferable), but rather their focal point and SA. They considered that the tools make monitoring easier: "providing more support for the controller must be a good thing" and decrease task load. However, due to RTS limitations, ATCOs couldn't make a proper comparison between the PWS solution and the eTBS operations from baseline. Still, they stated that if the system was working well, it would have added in some workload, but they feel it would be normal and manageable.	OK
		CRT-VLD-03-001C-HP-002	Situational Awareness is shown to remain at the same level or is improved	During debriefs, controllers stated that having the ELZ indicator makes their controlling tasks easier in terms of judging the situation, making it more clear more quickly than just "eyeballing" it (as is the case in today's operations). As such, the indicator supports controllers in drawing their mental picture and maintaining their SA. Moreover, according to the EOP survey, most ATCOs agreed that they could easily spot incorrect	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
				strip order and manage their strips to get reliable ELZ information during standard traffic and also breakoff/missed approach scenarios.	
		CRT-VLD-03-001C-HP-003	The likelihood and consequence of human error are assessed as remaining within acceptable levels	Not assessed	NOK
		CRT-VLD-03-001C-HP-004	The procedures are found to be acceptable by controllers	Procedures were generally very well accepted by controllers. The results of the End-of-Participation questionnaire show that most APP controllers strongly agreed that indicators procedures are acceptable. All APP controllers agreed that the Pairwise procedures for transitioning to 2NM MRS on final approach enables them to achieve the required spacing or separation. TWR controllers strongly agreed that procedures for normal operations are satisfactory.	OK
		CRT-VLD-03-001C-HP-005	The Method of Operations are found to be acceptable by controllers	Multiple abnormal scenarios were run during the two scenarios days (e.g., breakoff, medical emergency etc.), for most of which operating methods were deemed acceptable by ATCOs. Degraded conditions were not simulated in the RTS because the analysis of failure modes is incomplete.	OK
		CRT-VLD-03-001C-HP-006	The teamwork and communication enabled are shown to be acceptable	Not assessed	NOK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
		CRT-VLD-03-001C-HP-007	User roles and responsibilities are shown to remain acceptable	Though it was not intended to include the Group Supervisor (GS) position in this RTS, it was possible to replicate the GS's expected input. Further clarification of the GS's responsibilities (e.g., interacting with the system or making phone calls to the controllers) is still needed, which should be investigated in the future phases of development. During RTS debriefs, APP controllers highlighted the importance for GSs to be considered in training, for them to understand how to better support the FIN, who according to them is expected to get more work.	POK
		CRT-VLD-03-001C-HP-008	User Confidence is shown to remain within acceptable limits	During RTS debriefs, controllers stated that they feel the introduction of the IA tools as a replacement of the current eTBS setup is a very big shift (with the biggest change in HMI). According to them, the shift is bigger than the one they experienced when switching from TBS to eTBS, feeling more like the initial switch from DBS to TBS, and it will require in-depth training to ensure the safety of operations.	OK
		CRT-VLD-03-001C-HP-009	The tool is shown to support the controllers in their decision making processes	The vast majority of APP participants strongly agreed in the EOP questionnaire that the tools adequately support their decision making and their performance of controlling tasks safely and efficiently. Additionally, TWR controllers felt confident that the system would support them enough in	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
				proactively resolving any infringement of the required separation/spacing between aircraft.	
		CRT-VLD-03-001C-HP-010	The tool is shown to provide sufficient, clear, accurate and timely information to the controller	The majority of controllers reported feeling like the ELZ information supported their task performance and was presented at the right time to support decision making. In terms of accuracy, some APP controllers' feedback during debriefs explained that the LZ felt slightly inaccurate. It is possible that this behaviour could be due to the SIM design, i.e., the average speeds of aircraft on final approach not being representative of operational data and should be investigated.	POK
		CRT-VLD-03-001C-HP-011	Controller trust in the integrity of the tool support and reliance on indicators are shown to be acceptable	APP controllers agreed that the IA tools are good, useful tools overall, which most of them (67%, n=6) found easy to use, according to EOP responses. ATCOs who are a bit more cautious or inexperienced would be supported by the marker ("It brings the lower ones up" for those ATCOs with less experience, the indicator may help them to become more efficient by having something to aim for. However, they still may be less inclined to be on the indicator or very close to it due to concern of infringing the indicator and having to take recovery action as a result.	POK
OBJ-VLD-03-001C-SAF	To assess the impact of reduced MRS and PWS TBS	CRT-VLD-03-001C-SAF-001	The number of missed approaches due to insufficient spacing is no greater than in	The participating ATCOs did not indicate that missed approaches would be affected.	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
	on operational safety		currently operations		
		CRT-VLD-03-001C-SAF-002	Interoperability evidence can be produced to confirm that the elements of all solutions when combined do not degrade the level of safety.	The overall view from the ATCOs was that the interoperability of the solutions did not degrade safety.	OK
		CRT-VLD-03-001C-SAF-003	The combined solution and procedures cause no losses of separation in the demonstration exercise	The ATCOs did not report any LoS associated with PWS using the new MRS rules. There were 11 technical losses of MRS during the eTBS runs. Through expert judgement, it was identified that in all but one case of the eTBS losses; the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way. Based on this analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution.	OK
		CRT-VLD-03-001C-SAF-004	The combined solution and procedures cause no increase in the frequency of go arounds when compared to the reference scenario	See CRT-VLD-03-001C-SAF-001 above	OK
OBJ-VLD-03-001C-SEC	To assess the impact of reduced MRS and PWS TBS on operational security	CRT-VLD-03-001C-SEC-001	A Security Risk Assessment is carried out	In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with the SESAR methodology. As	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
				part of this, Security Risk Treatments were also applied.	
		CRT-VLD-03-001C-SEC-002	Security Risk Treatments are applied	In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with the SESAR methodology. As part of this, Security Risk Treatments were also applied.	OK
OBJ-VLD-03-002-001	reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines for different environmental conditions and aircraft types achievable reductions of separation minima	CRT-VLD-03-002-001	Method developed for RECAT-EU successfully applied	Lifetime reduction of long-lived vortices 22% (Medium) to 37% (Heavies) Circulation reduction by 50% for Medium behind Heavy Potential for reduction of separation minima by 15%	OK
OBJ-VLD-03-004-001	Capacity: To show potential for increased runway capacity with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-001	Potential for increased runway capacity, with at least 5%, with the introduction of the Integrated Runway Sequence Function has been demonstrated	The capacity can be improved by 12,5% with the introduction of IRSF	OK
OBJ-VLD-03-004-002	Environment: To show potential for decreased departure taxi	CRT-VLD-03-004-002	Potential for decreased departure taxi time with the introduction of the	No data for taxi-time improvements has been gathered.	NOK Not available in the technical set-up

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
	time with the use of the Integrated Runway Sequence Function		Integrated Runway Sequence Function has been demonstrated		
OBJ-VLD-03-004-003	Environment: To show potential for decreased arrival flying time with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-003	Potential for decreased arrival flying time, in relation with capacity increase, with the introduction of the Integrated Runway Sequence Function has been demonstrated	Potential to decrease arrival flying time while also increasing runway capacity with the use of IRSF has been demonstrated.	OK
OBJ-VLD-03-004-004	Environment: To show potential for avoiding noise sensitive area with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-004	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated	The potential to avoid noise sensitive areas has been demonstrated by replanning of arrival flights to land on departing runway or using RNP AR, thereby lowering the noise over noise sensitive areas.	OK
OBJ-VLD-03-004-005	Predictability and Punctuality: To show potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function	CRT-VLD-03-004-005	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data regarding predictability and punctuality was gathered with focus on difference in actual and Flight Plan or RBT durations as Flight Plans was not updated with information from the solution. Thereby no reduction in variance of difference in actual and Flight Plan or RBT durations can be presented. Predictability and punctuality were observed to be improved by the system when observations on ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.	NOK Not available in the technical set-up

Table 14: Summary of Demonstration Exercises Results

4.2 Detailed analysis of Demonstration Results per Demonstration objective

4.2.1 WP2 - EXE VLD-03-001C Detailed Demonstration Objectives Results

4.2.1.1 OBJ-VLD-03-001C-ACC Results

Impact of Runway Configuration and Wind Conditions

Survey responses report that all controllers found the Pairwise concept and functionality acceptable in all runway operating configurations. Similarly, all controllers also agreed that the Pairwise concept was acceptable across all wind conditions. Qualitative responses from controllers did not note any differences in the tool behaviour depending on wind or the runway in use and that the system would work effectively in any of these conditions in current operations.

Acceptability of HMI and Indicator Support

The eTBS system currently displays indicators for wake separation pairs, and for ROT pairs behind Upper, Heavy and Super aircraft where ROT is the largest constraint relative to the wake separation. Indicator types for all separation/spacing constraints are supported by the Heathrow Pairwise tool.

Across a range of operational contexts, controllers found HMI and indicator support acceptable. Controllers generally found the system and HMI intuitive and understood system behaviours. Regardless of the maximum constraint, the indicator support and HMI were found to be acceptable to controllers.

Support for aircraft when outside 20NM using the 3NM MRS indicator was considered acceptable by controllers, with two controllers somewhat agreeing to the overall acceptability in this scenario with the remaining four strongly agreeing. One controller commented that they can only give feedback on the 3NM MRS indicator based on earlier development simulations as they did not see it in this simulation. There were some runs where the wind conditions were such (i.e., tailwind) that even outside of 20DME the indicators were calculated greater than 3NM. Feedback from some controllers indicated that they did not feel the 3NM MRS indicator should be shown within 20DME even if follower aircraft was outside of 20DME as it was irrelevant. Similarly, indicator behaviour and HMI for dependent runway-constrained aircraft was acceptable to the controllers, but only three strongly agreed, whilst the other three rated this somewhat agree. One controller did not like the ELZ for dependent aircraft being displayed as '0.0' commenting that "0.0 works fine but it isn't particularly relevant to anything".

Some controllers observed indicators changing from a spacing to a dependent constraint for some aircraft pairs when the leader passes 1 DME. This is correct system behaviour and correctly reflects the constraints as they update. These scenarios shall be covered in training to ensure the controllers understand this system behaviour.

During the simulation, the controllers commented that they observed indicators pulling away when the lead aircraft passed 4DME. It was suspected that this behaviour may be caused by the aircraft

speed performance in the simulator. Therefore, it is recommended that a review of the simulator performance inside 4DME is conducted to ensure that it is consistent with operational data.

Acceptability of the Wake Breakthrough indicator (when an aircraft is detected within 0.5NM of a wake constraint when wake is not the maximum constraint) was generally accepted, as five of six controllers strongly agreed that HMI and indicator support was acceptable; however, one controller somewhat disagreed, arguing that 0.5NM is insufficient for a breakthrough, and that 0.75NM could be more suitable, to give an additional buffer for recovery. However, it should be noted that the Wake Breakthrough behaviour is the same in Pairwise as it is in eTBS today.

Acceptability of Procedures

In addition to the acceptability findings presented above in relation to the HMI and indicator presentation, participants also provided ratings on the associated procedures.

All participants were in agreement that the defined procedures are acceptable, as defined in the ConOps. Supporting comments suggest that the alignment of new procedures with those pre-established in eTBS operations increases their acceptability. Others had a more neutral response, stating that while they are “not ideal in each individual scenario, they provide consistent procedures across the board”.

One participant provided a detailed comment on the benefits and drawbacks of implementing simple and consistent procedures. Where this reduces the potential for human error and training complexity, it may also lead to potential operational inefficiencies due to controllers being required to initiate a go-around under certain conditions. Nevertheless, the participant responses to the defined procedures remains positive.

A component of the Heathrow Pairwise concept is the reduction of MRS from 2.5NM to 2NM on final approach, as well as rule changes to allow an earlier reduction from 3NM to 2.5NM in the RMA. To support this, operational procedures have been amended to protect against losses of separation. As such, validation participants were asked to indicate whether the combined procedures and indicator support provided are acceptable in supporting achieving required separation/spacings.

All responses were positive, with participants agreeing this support is acceptable for operations. Additional comments provided reinforcement that the support is “fail safe” and is “a logical procedure”. One controller commented that the ability to transition from 3NM to 2.5NM sooner than today is a ‘must’, particularly when certain wind conditions allow spacings below 3NM, as this spacing is difficult to achieve with the current rules.

One participant raised some concern that it may become easier to lose 2.5NM separation in the phase between turning onto the base leg and establishing on the final approach due to the line zero value and indicator for the 2.5NM constraint ‘tempting’ the controller to attempt to achieve this without having vertical separation. This scenario should be highlighted during training and there was a suggestion of introducing a standardised drop to a higher altitude than used in the current operation to give the final approach controller the option to use vertical separation. Being able to use vertical separation in such conditions is a considerable advantage; however, this may result in fewer continuous descent approaches, and some airlines may request to descend sooner.

From the perspective of tower controllers, both of the two tower controllers involved strongly agreed that procedures for all indicator types, including when aircraft ahead of the indicator are acceptable.

They also agreed that they were able to anticipate a possible deterioration in spacing/separation between aircraft.

Acceptability in Spacing Scenarios

As part of the End Of Participation (EOP) questionnaire, all participants provided ratings against the acceptability of the concept functionality against a full set of spacing scenarios which were simulated on two days of the exercise which focussed specifically on generating a range of operational scenarios.

Overall, eight specific functions were highlighted in the questionnaire which have been developed based on a human-centred design process to support the straightforward application of spacing changes within the Heathrow operational context.

Whilst none of the statements presented to the controllers received unanimous positive responses, the participants left several encouraging comments. For example, “although I hadn’t seen [the Heathrow Pairwise concept] for a while, I found it straightforward to pick up all of the above functionality”. Most neutral responses were from one participant, who commented that they “need more exposure to these events to be sure”.

Five out of six controllers agreed that they were able to input, edit and remove individual spacings effectively. One controller response was neutral, but commented that they need more exposure to using this functionality. For another controller, although they find the spacing functionality acceptable, they comment that this will “take some getting used to” as it is a new way of using ExCDS than in current operations.

During Runway inspections, it was noted that in the majority of cases, the lead aircraft will land before the follower has turned base leg and therefore the ELZ value will be lost (and therefore no indicator generated), or if the aircraft has turned base then the indicator and LZ will be lost. This was discussed during the debrief and all of the controllers felt this was not an issue, as they are able to remember the 4DME indicator value and ‘round up’, and if not, refer to the threshold value that is displayed on the designator. There was no concern regarding safety, due to the fact it is a spacing gap rather than a separation. This will also be covered during training.

Not all participants were exposed to the “PACK NEXT” functionality (in support of operations on the departure runway), or did not recall what function the term referred to when filling in the questionnaire, hence the two neutral responses. However, no objections were raised regarding this functionality during the simulation when it was tested.

Only the new Spacing Status Window received negative responses. The Spacing Status window, shown at the top of the FIN/INT ExCDS bay and displays current Spacing policy information. This was justified by comments stating that “the spacing status window does not display information in such a way that grabs my attention” and “I don’t find the box draws my attention to it. I don’t feel the way the data moves across is very intuitive”.

During the operational scenarios, a transition from VIS1 to VIS2 to LVPs and reverting back again was simulated. During the debrief the controllers commented that they found the indicator support to be acceptable. However, the comments made previously with regard to the information in the Status Spacing Window are also relevant here.

Another function that requires further refinement is the entry and removal of a closed runway exit spacing policy via the ExCDS interface. It was suggested that the interface design will be further refined following this validation exercise.

A discussion occurred between one of the observing Tower controllers and Approach during a scenario where the Tower calls and requests departure gaps during EMT. In current operations, the Tower will ask for the distance that they require when the lead aircraft reaches 4DME (for example, 6NM), which allows for compression between the leader and follower past 4DME. With the Pairwise concept, the Tower needs to request the gap relative to the runway threshold. This will be the value that is entered into the Spacing tool, and then the tool calculates the indicator distance to ensure that the threshold distance is met. Therefore, this is highlighted as a new way of operating between Tower and Approach and should be emphasised in training.

Acceptability in Other Scenarios

A blocked runway scenario was engineered on the second scenario day during the simulation. The Tower called Approach to inform that the runway was blocked due to an aircraft experiencing a burst tyre on landing. This resulted in several aircraft being instructed to conduct missed approaches and several being broken off the approach and then the remaining aircraft switched to the other runway.

The scenario worked successfully, with the controllers being able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs.

Both of the two tower controllers involved strongly agreed that procedures for a blocked runway with multiple missed are acceptable.

During the operational scenario testing days of the simulation, attempts were made to engineer several speed non-conformance scenarios. This proved to be difficult to set up in a simulated environment, however, the indicator procedures to adopt in a scenario of infringing an indicator were deemed to be acceptable by all participants.

A scenario of an aircraft without a wake vortex category was engineered during the simulation. As expected, the tool behaved as designed and did not generate an indicator for this aircraft. The controllers were able to apply the defined procedures which require extra spacing to be applied ahead of and behind the aircraft and found this to be acceptable.

Acceptability of the Early Line Zero Function

The Pairwise system provides an early indication of the required separation or spacing which is displayed in Early Line Zero (ELZ) on the aircraft track data block on the radar display. Controllers were presented with a range of statements relating to ELZ. Responses from controllers in this case were generally very positive, with participants agreeing that Early Line Zero is acceptable and supports their tasks.

One controller commented that *"I am not user of LZ, so ELZ is of limited benefit right now. I can see how it is helpful to others"*. The controller in question was asked to clarify this response, as ELZ is not present in eTBS today. The controller explained that, in current eTBS operations, they can make the base leg turn using their knowledge of RECAT-EU spacing and their own judgment.

During the simulation, the controller found that they were still using their current knowledge/judgement and not paying attention to the ELZ. They felt that additional exposure to the

function is needed to inform their acceptability. However, with the introduction of Pairwise, the complexity of the separation and spacing calculations will increase and ELZ is therefore expected to support the most efficient delivery.

As described previously, a blocked runway scenario was engineered which resulted in several aircraft being instructed to conduct missed approaches and several being broken off the approach and then the remaining aircraft switched to the other runway. The controllers were able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs and missed approaches.

4.2.1.2 OBJ-VLD-03-001C-EFF Results

Arrival Throughput Analysis

While a fully matched experimental design was planned, staffing limitations on the execution dates prevented this. It is expected that the objective data analysis was affected by this, particularly where findings were similar under reference and solution conditions. Due to preliminary findings, the experimental design was adapted part-way through the activity to introduce the moderate and heavy samples to the matched runs, which did not allow for them to be simulated in both directions. The findings are therefore sensitive to the influence of the small size of the data sample and disruption to the matched design. The quantitative results should therefore be interpreted with care and alongside the qualitative conclusions presented in this report.

The Pairwise solution is expected to deliver benefits due to:

- The change from the RECAT-EU to RECAT-EU-PWS wake turbulence separation scheme which would be expected to reduce the mean wake turbulence separation in all wind conditions (subject to the MRS constraint).
- The introduction of a 2NM MRS on final approach supported by tailored ROT indicators which would be expected to reduce the mean MRS or ROT spacing delivered at 4DME below the 3NM baseline values as the strength of the headwind conditions increase.

The results confirm the increase in landing rate in strong wind conditions. A considerably greater headwind component at all levels in this sample increases the proportion of non-wake pairs able to use less than 3NM spacing delivered to 4DME. Overall, a benefit to arrival throughput is seen under all conditions, although the difference under light and moderate wind is marginal.

However, a low or marginal benefit is seen in Light and Moderate wind conditions which is not fully in-line with the pre-validation expectations. The effects of the traffic mix and wind conditions are explored in the sections below.

Via debrief notes, it was reported that *“ATCOs feel that [Heathrow Pairwise] might bring about a benefit of greater consistency in terms of runway capacity. Some controllers today can be more conservative when aiming for separations, so therefore there is a bell curve of throughput delivery. Having indicators for all aircraft pairs may have the impact of ‘flattening the curve’”*.

The exercise activity was conducted using an interim set of adaptation that controls the Pairwise system and, in particular, the calculation of the indicator distances. Further refinements to this adaptation are expected in the future. It is possible that a degree of conservatism was present in the

ROT adaptation and there may therefore be scope for further optimisation subject to maintaining acceptable clearance to land behaviour for the system overall.

Analysis of Maximum Separation/Spacing Constraints

Due to the MRS minima reduction introduced as part of the concept, it is anticipated that the proportion of aircraft pairs with MRS as the maximum constraint at threshold will reduce. To confirm this, analysis was undertaken to highlight the shift in the proportion of aircraft with an MRS constraint with the change to Pairwise. Despite non-wake pairs not receiving indicators in the eTBS tool, it is possible to still determine maximum constraint for each aircraft pair from the platform logs. The tool logs were analysed to show the max constraint for aircraft under each scenario.

As can be expected for both tools, the proportion of wake pairs reduces in samples with a greater number of Medium aircraft; meaning that fewer lead aircraft generate a wake constraint. In these traffic mixes, the proportion of ROT spacing pairs increases in nearly all cases. For the 'MIXHM' samples, the wind conditions did not have a large impact on the proportion of wake pairs.

As the static MRS constraint under eTBS operations is 2.5NM at threshold, this is the maximum constraint for aircraft pairs that do not have a wake constraint (e.g. medium-medium pairs). This is demonstrated by the large proportion of MRS pairs in all conditions.

MRS constrained pairs were only present in strong wind conditions for Pairwise runs, as the wake and ROT values are reduced during periods where there is high headwind. As the MRS constraint at threshold is reduced to 2NM as part of the Heathrow Pairwise concept, ROT becomes the maximum constraint for non-wake pairs in all but the high wind conditions, where wake separation minima are reduced to a greater extent. This prompts a sizeable reduction in the proportion of MRS pairs, when compared to the equivalent eTBS run.

Delivery of Aircraft to Separation Minima

Instances were analysed in which a technical loss of MRS was recorded. These are referred to as "technical" losses as a simplistic analysis method was used, whereby radar tracks were used to identify potential losses of lateral separation (when aircraft had less than 1000ft vertical separation). These were then checked manually in the radar recordings to confirm if they were genuine losses.

There was a total of 11 technical losses of MRS during the eTBS runs while there were 0 technical losses in the PWS runs using the new MRS rules. Based on this brief analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution.

Through expert judgement, it was identified that in all but one case of the eTBS losses; the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way.

Delivery Conformance to Displayed Indicators

A greater proportion of aircraft are positioned on the indicator (0.0) under Pairwise operations compared to the eTBS reference, as well as an equal proportion positioned at +0.1NM. The impact of the inconsistent seating configuration between the runs in the same matched pair is likely to have had a confounding influence on this and should be considered.

In relation to the distribution where the leader aircraft is at 1DME, some large gaps (0.5-1.0NM) were seen only during Pairwise runs. A potential cause of this was highlighted in the observation notes, which noted “ATCOs commented that they observed indicators pulling away when the leader passed 4DME”. This was suspected to be a ‘simulator issue’.

With respect to those aircraft that infringed the displayed indicators (-0.1 to -0.5NM), system limitations required the first aircraft in the sample to land before the eTBS tool or Pairwise tool was activated. By this point, under both scenarios, participants had already positioned a stream of aircraft on the final approach behind this first aircraft. There were instances where participants found that the aircraft infringed their indicators when they appeared. As far fewer indicators are provided by the eTBS tool, far fewer instances of this were recorded under the reference scenario.

At 1DME, while the Pairwise functionality and procedures produced a more even distribution of conformance, a lesser proportion of aircraft were positioned on (or just behind) the indicators than under eTBS. A smaller number of infringements at this point were recorded under reference conditions (eTBS), although the cause of these could not be identified through log analysis.

4.2.1.3 OBJ-VLD-03-001C-ENV Results

The six sets of real time simulations provided hourly throughput values for eTBS and PWS. The average throughput increase for PWS over eTBS across these six sets was 0.44 movements per hour.

Due to the traffic samples selected to support the exercise, the analysis is based on two one-hour windows, 10:00 – 11:00 and 21:00 – 22:00. It is therefore assumed that the average impact during these hours apply between 06:00-22:00 UTC which will exclude the first hour of TEAM operations from the analysis. The base year for the analysis is 2019, since this is the last full year which is not impacted by Covid-19.

The total number of holding minutes saved as a result of PWS is calculated in two parts, the reduction in average holding time and the reduction in the number of flights that hold.

The reduction in average holding time for an hour is calculated as the number of extra movements multiplied by the average holding time per holding flight in the hour. This was calculated for all hours (06:00 UTC onwards) in which holding occurred throughout 2019. Summing these gives the total holding minutes that could be saved for flights that hold.

In addition, it is assumed that a reduction in holding time will reduce queue lengths, leading to a reduction in the number of flights holding. The introduction of eTBS at Heathrow delivered a theoretical 1.1 movements per hour and resulted in a 13% reduction in the proportion of flights holding. It is assumed that the reduction in the number of flights holding at Heathrow under PWS can be estimated as a direct proportion of that the benefit observed for eTBS i.e. PWS will deliver a 5.2% reduction in the number of flights holding because $\frac{0.44}{1.1} \times 13\% = 5.2\%$. The estimated reduction in the number of flights holding is multiplied by the number of arrivals in 2019 (238,818) and the average holding time per arrival flight (3.32 minutes) to estimate the number of minutes holding saved by reducing the number of flights in the stacks.

Combining the two values gives the total holding minutes that could have been saved for 2019, which can then be converted to fuel savings on the assumption that the average fuel burn per minute of holding is 63.8kg/min across all Heathrow arrivals (based on airborne holding at FL80 and a typical Heathrow aircraft fleet mix).

This translates to an average of 14 seconds holding saving per flight and 14.84kg fuel saved per flight. Using the direct link between fuel burn and the amount of CO₂ produced (3.15 times the mass of fuel burnt), this equates to 46.73kg of CO₂ saving per flight.

4.2.1.4 OBJ-VLD-03-001C-HP Results

For Human Performance related objectives, please refer to the HPAR [43] for a description of the findings.

4.2.1.5 OBJ-VLD-03-001C-SAF Results

Controller Feedback

This assessment has assessed the safety related questions and has considered the results from the Sector Participants. The questions have not been broken down by run.

Except for three essay-style questions, the questions were in a multiple-choice format with up to three options. Where half or more of the responses from the controller group selected favourable results, the overall status of the question has been marked as OK.

The questions addressed the following three key areas:

- User Interface and Procedures
- Losses of Separation (LoS)
- General Safety Impact

User Interface and Procedures

The purpose of the general safety questions was to assess the controller's views on tool, concept and functionality. Subsequently, the questions focus on the interface and basic procedures (it is noted that there is some overlap with the Human Factors (HF) assessment). The results are overwhelmingly positive. Negative responses are due to the specific scenario not having been seen by a controller.

Loss of Separation

The purpose of the questions relating to LoS was to understand how these would be affected compared to the current operation. Therefore, the questions focused on the flight segments where the indicators would be shown, as this is where the concept primarily differs from eTBS.

In general the feedback relating to LoS was positive with no LoS being recorded in relation to the indicator positions.

Consecutive Runway Switch

Procedures have been written (in coordination with Safety) for two consecutive switches which will be safety assured. The first aircraft should be switched over, and then when indicator is displayed, the second aircraft would be switched over while still applying the rules for indicator infringement.

During the operational scenario days, a blocked runway was simulated where consecutive runway switches were tested. Whilst the controllers did not have any negative feedback about the defined procedures for consecutive switches, the scenario did raise discussions regarding the infringement procedures when an aircraft is 0.5NM ahead of an indicator and requires breaking off the approach (refer to Section 4.2.1.1).

Potential Increase of LoS

When asked whether the concept would increase the number of LoS, the results were mostly positive. There were 11 technical LoS during the eTBS runs while there were 0 technical LoS in the PWS runs.

Through expert judgement, it was identified that in all but one case of the eTBS losses, the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way. Based on this analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution.

General Safety Impact

The remaining questions were open-ended to attempt to explore any aspect of the design that the controller may perceive to be potentially safety related. There was no negative feedback with regards to the general safety impact question.

4.2.1.6 OBJ-VLD-03-001C-SEC Results

In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with the SESAR methodology. As part of this, Security Risk Treatments were also applied. In line with SESAR guidance, the detailed content of this assessment will not be provided as part of the data pack for sensitivity reasons.

4.2.2 WP3 - EXE VLD-03-004 Detailed Demonstration Objectives Results

OBJ-VLD-03-002-001 comprises the "Reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines for different environmental conditions and aircraft types" and the "Assessment of achievable reductions of separation minima". Additionally, we report here on the "Technical plate line design for permanent deployment at an airport" including the "Material needed for authority approval for the installation of plate lines at an airport location" and "The installation of the plate prototype in a suitable environment."

Reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines.

The analysis is based on a measurement campaign that has been accomplished from 6 May 2019 until 28 November 2019 at Vienna International Airport in the SESAR Joint Undertaking "Increased Runway and Airport Throughput" project (PJ.02 EARTH). The following analysis is described in detail in Ref. [28]. During the campaign at Vienna airport two temporary plate lines were erected below the glide path to runway 16 and wake vortex behaviour was gathered employing three wind lidars complemented by a suite of meteorological instrumentation (see Figure 2 and Figure 3).

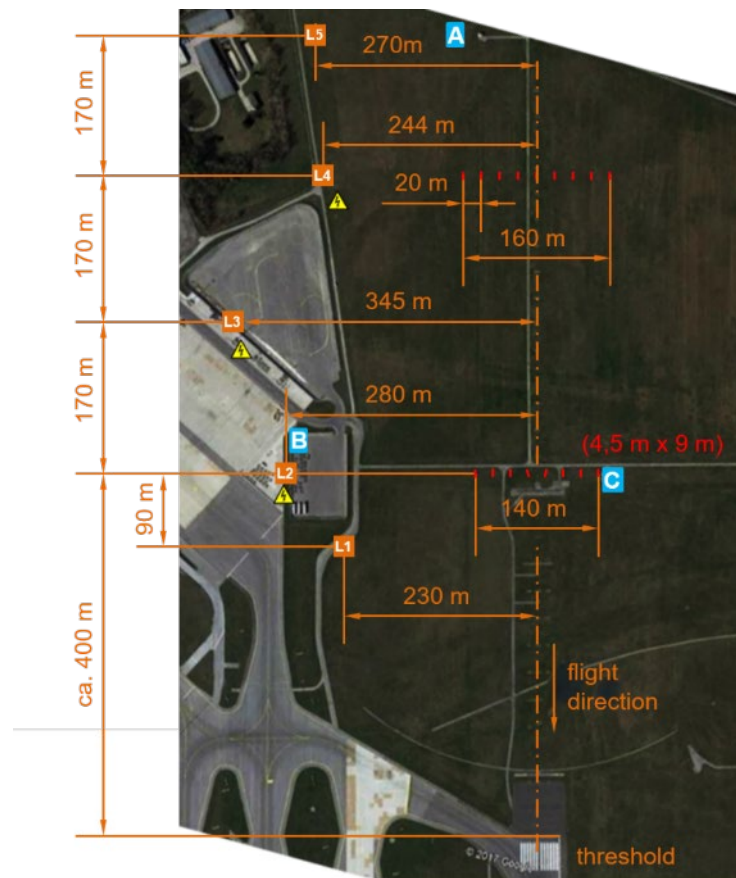


Figure 2: Positioning of plate lines (red dashes) and lidar measurement positions L1 to L5 (© Google 2017).



Figure 3: Overflight of A380 of plate line 2 next to the localiser.

Wake vortex behaviour of about 9,500 approaches has been collected in five different lidar measurement planes L1 to L5 (see Figure 2) covering the area in which wake vortices may rebound to the approach path corridor. From these over 1000 wake vortex evolutions with and without plate lines have been processed and used for the current analysis.

The developed evaluation strategy focused on safety aspects:

- The conducted analysis employs an aircraft safety corridor extending ± 50 m from the runway centreline. Vortex measurements outside that safety area are neglected for the analysis of the lifetime reduction by the plates. However, circulation reduction can only be evaluated if the vortices are considered throughout their entire lifetime. This requirement is met by

considering only vortices where the last measured location is situated within the safety corridor. The sensitivity to the width of the safety corridor turned out to be weak. A larger safety corridor slightly decreases the measured plate line effectiveness, because additional plates ahead of a vortex strengthen the plate-induced vortex decay.

- The data indicates that vortex decay is correlated with headwind speed. Because strong headwinds support the transport of end effects (occurring during touchdown and accelerating vortex decay) into the measurement planes, cases with headwinds stronger than 2 m/s are excluded for the further analysis. Encounter frequencies and go-around rates are highest at weak headwinds or even tailwinds [29].
- The analysis combines data of all the available lidar measurement planes, because the accelerated vortex decay should be effective all along the stretch where rebounding vortices may reach up to the flight corridor. Given the large scatter of wake vortex lidar data, the data samples collected in the five individual lidar planes appeared too small to support conclusive results for each individual plane.
- To enable the comparison of wake vortices generated by different aircraft types, the data characterizing vortex decay is partly normalized employing aircraft parameters retrieved from the Mode-S protocol and aircraft masses provided by Austrian Airlines.
- The analysis evaluates the above median lifetime reduction of wake vortices at an advanced state of decay. For vortices at an advanced state of decay (circulation bins below 150 m²/s and normalized circulation bins below 40% of the initial circulation) the median, the 75th percentile, and the 95th percentile of the vortex lifetime are considered. To condense the results to a single percentage of lifetime reduction, the 18 values resulting from three dimensional circulation bins and three normalized circulation bins with three percentiles, respectively, are averaged.
- The circulation reduction is considered for vortex lifetimes around 60 s for Medium vortex generating aircraft and around 120 s for Heavies. Again, the relative circulation reductions achieved for the three selected percentiles are averaged into a single value.
- Finally, the Wilcoxon rank-sum test is used to assess whether the differences of the lifetime distributions with and without plate lines are statistically significant or not. Further, margins of uncertainty of the median lifetime reductions are determined with 95% confidences.

As an example of the measurement results Figure 4 depicts probability density distributions (PDD) of the vortex lifetimes for different circulation ranges. The PDDs for circulations above 250 m²/s with and without plate lines are almost identical indicating that the statistical basis for their further development is sound. With decreasing circulation strength, the PDDs with and without plate lines diverge evermore which is also seen in the median values of the PDDs indicated by vertical lines. The Wilcoxon rank-sum test indicates that the PDDs for circulations below 200 m²/s differ with extremely high statistical significances with and without plate lines. Similar characteristics are also observed for the individual aircraft types.

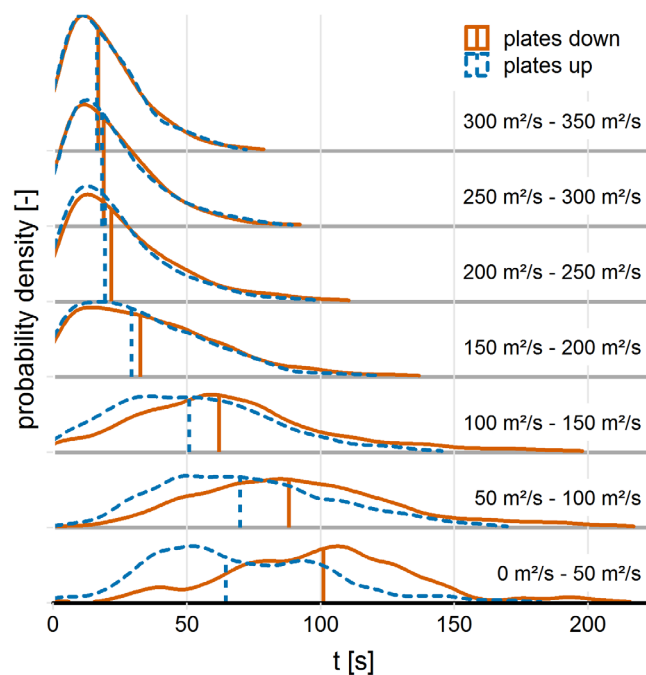


Figure 4: Probability density distributions of vortex lifetimes for different circulation bins for different aircraft of weight classes J, H, M employing the ± 50 m safety corridor for headwinds lower than 2 m/s. Vertical lines indicate the median values.

Following all the above listed criteria, the lifetime of the vortices in the safety corridor is reduced on average by 22% for 420 landings comprising Medium, Heavy, and Super weight class aircraft. For this 456 vortex pair evolution measurements with plate lines and 472 vortex pair evolutions without plates have been considered. The median lifetime reductions according to the Wilcoxon test range from 21% to 30%. The average circulation reduction around vortex ages of 120 s, corresponding to the ICAO separation for Mediums behind Heavies, amounts to 66% (32% for the 95th percentile).

It is found that increased environmental turbulence reduces wake vortex lifetimes by the same order of magnitude as the lifetime reductions achieved by the plate lines. The circulation and lifetime reduction potentials of plate lines appear to be similar in low and high-turbulence conditions. So, the highest potential for the mitigation of wake vortex risks lies within low wind and low turbulence conditions where without plate lines the longest-lived vortices occur and are leading to the highest encounter risks - just those reasonable worst-case environmental conditions for which the plate-line concept was developed in the first place.

The question how many plate lines are required to mitigate wake turbulence risks within the complete area where wake vortices may rebound to the flight path and cause vortex encounters is investigated by comparing measurements with one and two plate lines. The data suggests that a single plate line might be a little less effective than two lines but should be sufficient to trigger most of the desired favourable effects. Obviously, the propagation speed and outreach of the disturbances triggered by the plates are quite high.

The mitigation potential of wake turbulence risks via plate lines is considered for the most frequent aircraft at Vienna airport for three different weight categories of the RECAT-EU scheme. As representative of the ICAO weight category Medium and category D "Upper Medium" of the RECAT-EU scheme, 348 approaches of the A320 aircraft corresponding to 337 vortex pair evolutions with plate

lines and 388 vortex pair evolutions without plates have been assessed. For this smaller aircraft type circulation and lifetime reductions are less pronounced than for larger aircraft, because the interaction of the smaller vortices with the plates sets in later, leading to an overall reduced plate effect. The circulation of the A320 vortices is reduced on average by 8% at vortex ages around 60 s corresponding to radar separation. The vortex lifetimes are reduced on average by 18%, whereas the medians of the lifetime reductions vary according to the Wilcoxon rank-sum test between 17% and 27%. Considering only those measurement planes where intense vortices might rebound to the flight corridor, the average lifetime reduction is increased to 22%.

Within the weight category Heavy and category C “Lower Heavy” of the RECAT-EU scheme the B767-300ER was the most frequently captured aircraft type with 39 approaches. Based on 54 vortex pair evolutions with and 52 vortex pair evolutions without plate lines the reduced vortex lifetimes average to 23% with a confidence interval of the median of 18% to 36%. Within the ICAO separation relevant vortex age bins centred around 120 s the circulation is reduced on average by 53%.

The B777-200ER with 30 landings is the most frequent representative of the RECAT-EU scheme B “Upper Heavy”. For this aircraft type 41 vortex pair evolutions with plate lines are compared to 38 vortex pair evolutions without plates. The longest-lived B777-200ER vortex reaches a lifetime of 315 s. The average circulation reduction of 48% and the average lifetime reduction of 37% are quite high and backed up by the Wilcoxon test notwithstanding the relatively small sample size.

Despite the relatively high scatter of individual lidar circulation measurements, the presented statistics appear sound. So initially, the percentiles for the cases with and without plate lines proceed almost identically, demonstrating that random fluctuations stemming from varying environmental conditions and stochastic vortex behaviour as well as measurement uncertainties have smoothed out. Then the curves split up into λ -shaped legs when the plate induced decay comes into effect. This instant coincides with the time when the Wilcoxon test attests the transition from statistically similar vortex age distributions to distinctly different distributions with high confidences transitioning from p-values like 0.7 to 10^{-10} .

In summary, it can be concluded that the plate lines substantially reduce both the lifetime of wake vortices as well as their circulation at vortex ages relevant for aircraft separations in a safety corridor along the final approach path. The above median lifetime reductions increase with aircraft size from 18% for the A320 to 37% for the B777-200ER. If we exclude flight altitudes not impaired by energetic rebounding wake vortices, the A320 vortices experience almost the same lifetime reduction of 22% as the vortices shed by B767 aircraft with 23%. For the two investigated Heavy aircraft types the mean circulation reduction amounts to 50% assuming a 120 s separation to following Medium weight class aircraft.

Assessment of achievable reductions of separation minima

Now the Vienna data base is analysed in order to assess the potential for reducing minimum aircraft separations facilitated by plate lines during approach and landing following the RECAT-EU and RECAT-EU-PWS methodologies for revised wake turbulence categorization. In the following, these two complementary methods are mostly considered together and are termed RECAT-EU(-PWS) for simplicity.

For this purpose, the RECAT-EU(-PWS) methodology is adopted as close as possible in order to estimate most realistic potential capacity gains that already meet to a large extent the requirements for future approval by the authorities and operational implementation. The method to estimate the potential for reduced separations with plate lines in ground proximity with respect to RECAT-EU(-PWS) is described in detail in Refs. [30], [31]. Wake vortex risks along higher parts of the glide path, where

plate lines have no effect on the wake vortices, are considered as well. The final separation reduction potential results from the maximum separations found either in ground proximity with the plate line or out of ground effect on the glide slope without plate line effects.

In order to ensure that the analysis of the aircraft separation reduction potential is valid, it is verified that other parameters controlling wake vortex decay like wind speed, atmospheric turbulence, thermal stratification, and flight altitude above ground reside in similar ranges with and without the plates [31]. It is shown that wind and turbulence conditions both would even support slightly faster decay without the plates such that the environmental conditions for the assessment of the separation reduction potential may be clearly rated conservative.

Prior to the very analysis, the measured single vortex evolutions were screened by excluding cases with headwinds above 2 m/s, featuring premature vortex decay caused by so-called end effects triggered during touchdown. Further, those vortices were excluded that are quickly and irrevocably advected out of a safety corridor around the glide path, because these are irrelevant for the encounter risks of following aircraft.

Next, the analysis follows the steps of the RECAT-EU(-PWS) method to generate the so-called reasonable worst-case (RWC) decay curve (see Figure 5). First, the vortex age of the considered vortex evolutions is adjusted such that the vortex evolutions commence at a height of one wing span of the vortex generator aircraft above ground. Then, the measured circulation evolutions are fitted by a two-phase decay model in order to smoothen the scatter of the lidar data and to enable extrapolation to low circulation values. In order to combine the data originating from 12 different aircraft types, the two-phase decay curves are normalised based on the estimated initial values of the circulation and the vortex separation.

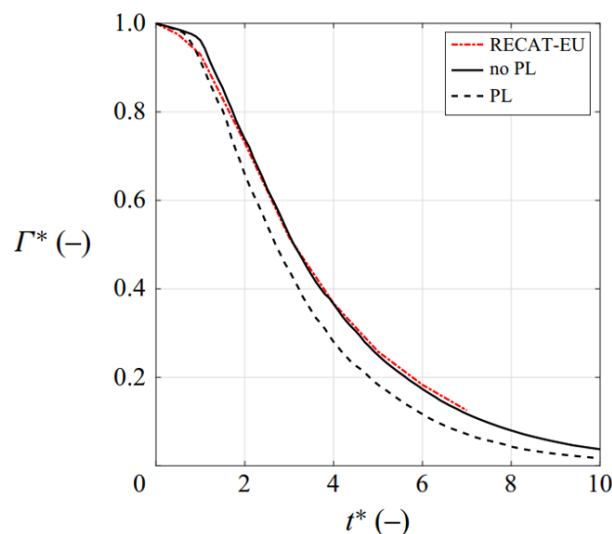


Figure 5: Normalised reasonable worst-case circulation decay curves from RECAT-EU(-PWS) and the corresponding decay curves established from the Vienna data without and with plate lines.

The resulting median decay curve is fitted to the RECAT-EU(-PWS) reasonable worst-case curve by selecting the cases with measured lifetimes extending beyond 3.5 vortex timescales. As reasonable worst-case atmospheric conditions were given preference already for both execution and processing of the Vienna measurements, the selected vortices correspond to 72% of the Vienna data; a much higher fraction compared to the top 2% of the longest-lived measurements resulting from a lifetime threshold of five vortex timescales applied to the over 100,000 tracks collected at London Heathrow airport for RECAT-EU(-PWS). While the number of the individual circulation decay curves generated by

Heavy category aircraft types is lower here than that considered in the RECAT-EU(-PWS) safety case, the lidar data also allowed establishing decay curves for a Medium category aircraft type. Nonetheless, the good agreement of the reasonable worst-case decay curves made up of the different data sets provides good confidence that the applied methods are actually equivalent.

The time-based separation reduction potential enabled by the plate lines is established in analogy by selecting the top 72% of the longest-lived vortex evolutions with upright plates. It is translated into spatial minimum separations of the RECAT-EU(-PWS) categories using typical parameters of the leading and following aircraft within the respective categories of the separation matrix. The sensitivity of the resulting minimum separations to the required parameters aircraft gross mass, air density, initial vortex separation, and approach speed turns out to be minor and not critical for the robust assessment of the aircraft separation reduction potential.

Leader / Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
		A	B	C	D	E	F
Super Heavy	A	2.6 NM -0.4 NM -13.3 %	3.4 NM -0.6 NM -15.0 %	4.4 NM -0.6 NM -12.0 %	4.4 NM -0.6 NM -12.0 %	5.2 NM -0.8 NM -13.3 %	6.9 NM -1.1 NM -13.8 %
Upper Heavy	B		2.6 NM -0.4 NM -13.3 %	3.5 NM -0.5 NM -12.5 %	3.5 NM -0.5 NM -12.5 %	4.4 NM -0.6 NM -12.0 %	6.0 NM -1.0 NM -14.3 %
Lower Heavy	C			2.6 NM -0.4 NM -13.3 %	2.6 NM -0.4 NM -13.3 %	3.5 NM -0.5 NM -12.5 %	5.2 NM -0.8 NM -13.3 %
Upper Medium	D						4.3 NM -0.7 NM -14.0 %
Lower Medium	E						3.4 NM -0.6 NM -15.0 %
Light	F						2.6 NM -0.4 NM -13.3 %

Table 15: Distanced-based aircraft separation minima with plate lines and differences to RECAT-EU scheme. Empty fields indicate minimum radar separation.

Table 15 outlines the resulting distanced-based separation minima with plate lines in nautical miles within the RECAT-EU separation matrix in bold face. Listed below the minimum separations are the differences to the respective RECAT-EU minimum separations as absolute values in NM and as percentages. The aircraft separation reduction potential varies between 12% and 15% depending on the respective aircraft category combination.

As the efficacy of the plate lines appears to be higher for larger leading aircraft, the aircraft separation reduction potential based on the reasonable worst-case decay curve established from measurements of the B772, taken as representative of the RECAT-EU(-PWS) leader category Upper Heavy, would amount up to 20% (not shown). Focusing in any future lidar measurement campaign on

Heavy aircraft, as done within the RECAT-EU(-PWS) safety cases, may presumably increase the separation reduction potential of the plate lines.

Applying the same methodology as described above, the potential for reduction of minimum separations is evaluated for the RECAT-EU-PWS separations. Figure 6 depicts the absolute and relative separation reduction potential for the 86 considered aircraft types.

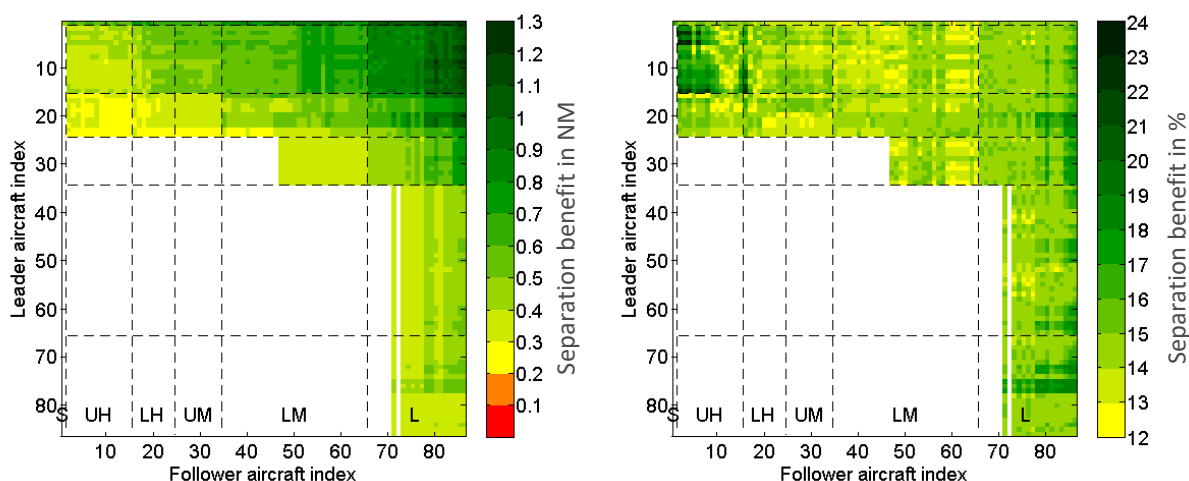


Figure 6: Separation reduction potential with plate line for RECAT-EU-PWS separation minima; left absolute in NM, right relative in percent.

The aircraft types are depicted only by their index as a labelling with the exact name would be barely readable. Low numbers indicate heavy aircraft and high numbers indicate light aircraft. However, in order to give a better overview, the boundaries of the RECAT-EU aircraft categories are shown by the dashed lines.

Figure 6 shows an absolute reduction potential of circa 0.4 NM to 1.3 NM, which corresponds to approximately 12% to 24%. The average over all aircraft pairings is 14.8%. Hence, the reduction potential shown here is on the order of magnitude of the reduction potential evaluated for RECAT-EU (Table 15) and even higher for some aircraft pairings.

With a risk assessment employing the rolling moment coefficient RMC to characterize encounter severity and the traffic mix from the top 25 ECAC airports to characterize the frequency of occurrence, the risk of the separation schemes under worst-case conditions was investigated following the method employed for the RECAT safety cases. It was found that the installation of plate lines could substantially reduce wake vortex encounter risks for all three considered separation schemes (ICAO, RECAT-EU, RECAT-EU-PWS), bringing the encounter risk of RECAT-EU-PWS down to a risk level even below that of RECAT-EU (and that of RECAT-EU for the greater part down below that of ICAO).

Also, the out-of-ground effect (OGE) analysis, representing the flight situation at 4 NM before threshold, follows the RECAT-EU-PWS safety case report. Circulation decay is computed for all 86 considered aircraft using the deterministic version of the P2P wake vortex prediction model [31] for RWC atmospheric conditions represented by a turbulence eddy dissipation rate $EDR = 4 \cdot 10^{-4} \text{ m}^2/\text{s}^3$ and a thermal stratification in terms of the Brunt-Väisälä frequency of $N = 10^{-2} \text{ 1/s}$.

Leader / Follower	Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
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		A	B	C	D	E	F
Super Heavy	A	3.0 NM -0.0 NM -0.0 %	4.0 NM -0.0 NM -0.0 %	5.0 NM -0.0 NM -0.0 %	5.0 NM -0.0 NM -0.0 %	5.9 NM -0.1 NM -1.7 %	7.9 NM -0.1 NM -1.3 %
Upper Heavy	B		2.6 NM -0.4 NM -13.3 %	3.8 NM -0.2 NM -5.0 %	3.9 NM -0.1 NM -2.5 %	5.0 NM -0.0 NM -0.0 %	7.0 NM -0.0 NM -0.0 %
Lower Heavy	C			2.6 NM -0.4 NM -13.3 %	2.6 NM -0.4 NM -13.3 %	3.8 NM -0.2 NM -5.0 %	5.6 NM -0.4 NM -6.7 %
Upper Medium	D						4.3 NM -0.7 NM -14.0 %
Lower Medium	E						3.6 NM -0.4 NM -10.0 %
Light	F						2.6 NM -0.4 NM -13.3 %

Table 16: Distanced-based aircraft separation minima with plate lines and differences to RECAT-EU scheme considering OGE limitations of separation reduction. Empty fields indicate minimum radar separation.

For every follower aircraft the minimum separation distance OGE between the aircraft pairings is adjusted such that the highest rolling moment coefficient (RMC) occurring under RECAT-EU-PWS is not exceeded using an airspeed of 160 kts. Then an additional separation of 0.5 NM is added to all separations as a buffer to consider the “compression effect” occurring on the way to the runway threshold.

For the RECAT-EU aircraft categories the respective worst-case pairings within one category define the minimum separation for the complete category. The final separation reduction potential with plate line shown in Table 16 corresponds to the maximum separation found in ground proximity and out-off-ground effect along the glide path. Depending on the particular RECAT-EU category combination, the aircraft separation reduction potential now ranges between 0% and 14%. The average benefit for the operationally relevant Heavy-Heavy and Heavy-Medium pairings amounts to 7.5%.

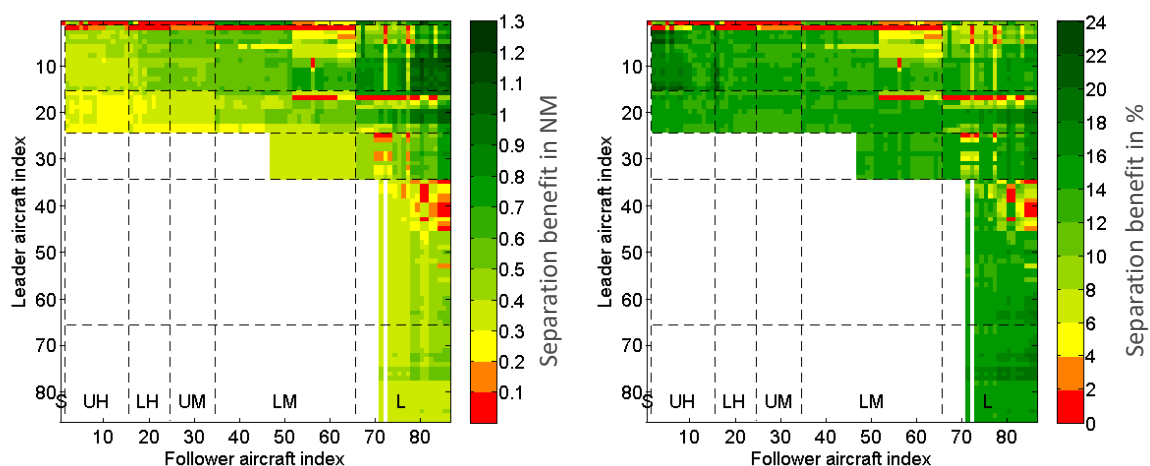


Figure 7: Separation reduction potential with plate line for RECAT-EU-PWS separation minima considering OGE limitations of separation reduction; left absolute in NM, right relative in percent.

Figure 7 depicts the separation reduction potential with plate line for the RECAT-EU-PWS separation minima considering the restrictions of the OGE analysis. The absolute separation benefits on the left are ranging from 0 NM to 1.22 NM with an average 0.45 NM corresponding to relative separation benefits on the right ranging from 0% to 23.8% with an average of 13.1%. The OGE analysis restricts the plate benefits obviously much less for RECAT-EU-PWS than for RECAT-EU as only a few leading aircraft types (see red or orange pairings in Figure 7) restrict some of the category combinations listed in Table 16.

It can be concluded that even though plate lines are only effective close to the ground, they still support a potential reduction of the separation further up on the glideslope. For most aircraft pairings, the in-ground-effect (IGE) case is dimensioning the wake vortex separation, which allows a potential reduction of the separation even for the out-of-ground-effect (OGE) case without compromising safety. When using RECAT-EU as reference, substantial benefits can only be gained for some – albeit relevant – aircraft category combinations. When using RECAT-EU-PWS as reference, for most aircraft pairings, benefits of about 0.5 NM separation reduction seem to be possible when using plate lines. As OGE wake vortex transport is the relevant mechanism guaranteeing safe separations, further OGE separation analysis may be needed for a safety case that will make this separation reduction potential available at congested airports.

In order to assess the potential of plate lines for dynamic pairwise separations (RECAT III) the Wake Vortex Prediction System (WSVS) developed by DLR is used. The study employs twelve months of traffic and weather prediction data collected at Vienna International Airport as described in [33]. The meteorological conditions are taken from operational predictions of the Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) with a model output interval of three hours. The considered arrival traffic consists of 106,293 approaches and landings of 94 different aircraft types on the runways 11/29 and 16/34 during the months November 2017 to October 2018. With these input parameters the P2P probabilistic wake vortex model predicts wake vortex evolution within 16 gates (WSVS prediction planes) along the final approach.

The distance between the gates is 1 NM along the glidepath and is reduced in ground proximity first to 1/3 NM and then to 1/6 NM to properly resolve the interaction of wake vortices with the ground. The probabilistic bounds of vortex position and strength predicted by P2P are expanded by the safety area around a vortex that must be avoided by follower aircraft for safe and undisturbed flight employing the simplified hazard area prediction model SHAPe. The instant when all the resulting safety ellipses along the glideslope do not overlap anymore with the elliptical approach corridor defines the temporal minimum wake-vortex separation between an individual aircraft pairing. For operational purposes, the maximum of three time thresholds, the WSVS separation, the minimum radar separation, and the runway occupancy time, would then constitute the applicable separation.

For this study a parametrization of the plate line effects has been developed using the wake vortex measurement data collected at Vienna airport. The plate line parametrization uses a differential extension of the two-phase circulation decay model [32] with an earlier onset of rapid decay (rapid decay without plates is initiated at an altitude of one vortex separation above ground, with plate lines it starts already 10 m higher) and a by 48% increased turbulent viscosity determining the vortex decay rate. The plate disturbances propagate at a speed of 8.0 m/s and the probabilistic envelopes for vortex circulation are widened by 2%.

Figure 8 shows exemplarily normalized circulation decay of wake vortices generated by B763 aircraft without (left) and with plate lines (right), where symbols denote lidar measurements and lines the P2P predictions.

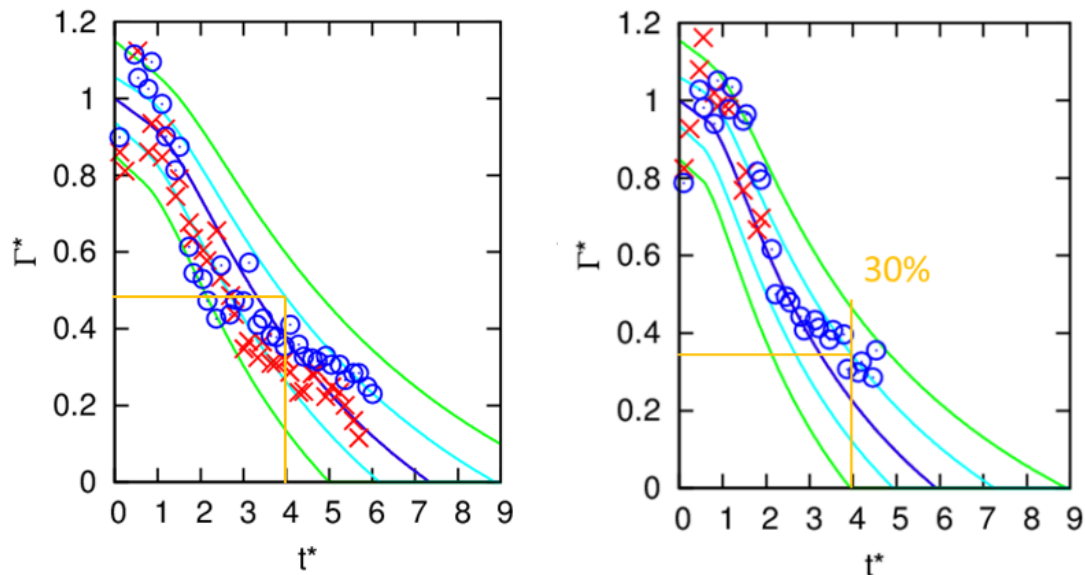


Figure 8: Probabilistic P2P predictions of normalized circulation decay of B763 aircraft without plates (left) and with plates (right) in a measurement plane at 170 m upstream of plate line 2. Symbols denote lidar measurements, dark blue lines the deterministic predictions and the light blue (green) lines denote the probabilistic 1- σ (2- σ) envelopes.

The yellow marks indicate that at a relevant vortex age of 4 vortex time units (vortex age around 100 s) the upper probabilistic envelope for circulation used by the WSV (light blue line) is reduced by about 30% compared to the case without plates.

The WSV analysis shows that plate lines reduce the longest-lived wake vortices under RWC conditions in ground proximity that are not blown out of the glide path corridor by crosswinds with a strength below 2 m/s. As RWC conditions in terms of turbulence and thermal stratification occur only in about 2% of the time, the corresponding separation gains for pairwise dynamic separations by plate lines are also quite limited and amount to about 2%.

Technical plate line design for permanent deployment at an airport

To develop a technical design of the plate lines for the permanent installation at airports, a three-stage design process was carried out consisting of i) the development and prioritisation of requirements, ii) the development of 15 potential designs and selection of four most promising ones, and iii) the detailed design and strength analysis of the four remaining concepts enabling the selection of the best design. This design process is detailed in deliverable PMP.006 [34].

In the first design phase, requirements were gathered in several exchanges between DLR and selected experts of ACG. Figure 9 depicts the resulting requirements ranked according to their relevance rated by the experts from ACG.

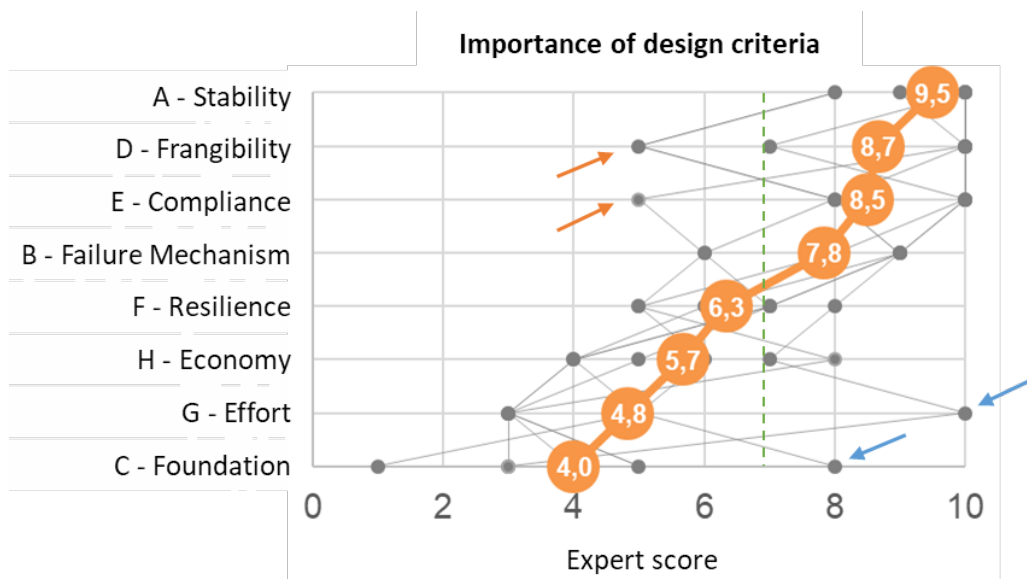


Figure 9: Plate design criteria ranked according to relevance.

Second, based on a morphological analysis a longlist of 27 plate design ideas was developed and characterised by a fact sheet. Simplified analytical stress calculations considering the wind loads defined by different norms (ÖNORM EN 1991-1-4:2013, ÖNORM B 1991-1-4:2013, ICAO Doc 9157 Part 6, Ch. 3.2) reduced the number of design ideas to 15 potential designs shown in Figure 10. The 15 viable shortlisted designs were discussed in detail and rated in a formalized voting process by experts based on the design criteria with their respective weights. The resulting scores are listed in Figure 10 below the designs.

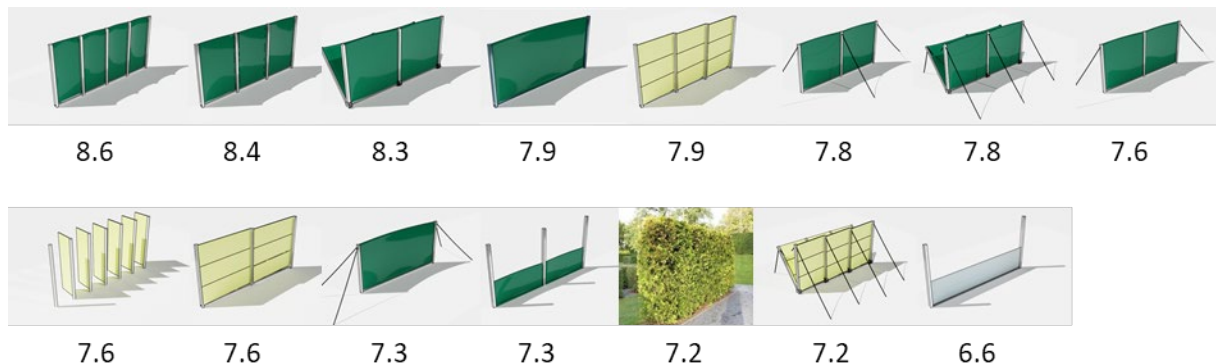


Figure 10: Fifteen plate line designs on the shortlist with expert scores.

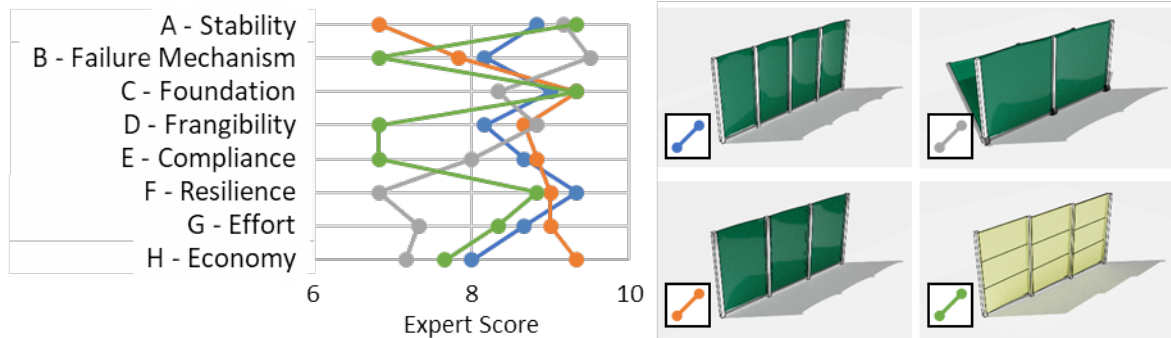


Figure 11: Expert scores for the four selected designs.

The four most promising designs, which are shown in Figure 11 together with the respective unweighted ratings of the eight requirements, were selected for further development. These remaining designs are: five masts covered with truck tarpaulin (blue scores), four masts with tarpaulin (orange), movable three-mast system with reset device and tarpaulin (grey), and four masts with panels (green).

In the third step, the four selected designs were matured into technical solutions and modelled in detail using finite element methods (FEM). As the design with four masts with tarpaulin turned out not to be stable enough, three technical design solutions for the plate lines remained. The elaborated solutions were presented in another expert workshop with DLR and ACG, where two final designs were deemed suitable for installation at an airport: five masts with tarpaulin and four masts with panels.

In a next step, a consultation with the mast manufacturer Lattix (Sweden) provided guidance for the choice of the final design leading to the selection of the four-mast solution with panels. Figure 12 shows the plate prototype installed at the antenna test centre Rauchenwarth close to Vienna airport in January 2023. The plate design consists of four aluminium lattice masts 4430 with a side length of 300 mm which are passively safe and certified for frangibility. Lattix masts are used at numerous airports worldwide and are installed even with plates for visual cover at Shanghai Hongqiao International Airport. Nine ALUCORE aluminium honeycomb composite panels are hooked in to the mast connectors. To guarantee frangibility the plates don't stiffen the plate construction but would release from the connectors easily and fall to the ground once an airplane would hit a mast.



Figure 12: The plate prototype installed at antenna test centre Rauchenwarth close to Vienna airport is inspected by international visitors.

Material needed for authority approval for the installation of plate lines at an airport location

The material compiled for authority approval for the installation of plate lines at an airport location comprises the detailed documentation of the development process described briefly in the previous section [35]. In particular, the document details how the design responds to the eight identified requirements. It also describes the computations of plate stability against heavy storms and the measures that guarantee frangibility. This is complemented by technical drawings of all parts and corresponding part lists as well as instructions for the installation of the foundation and the plate. Based on this documentation an external expert opinion [36] was commissioned which led to several minor adjustments of the plate design and the dimensioning of the foundation. Ref. [37] confirms that all expert comments have been considered in the plate design described in Ref. [35].

This comprehensive material corresponds to the documents that the Austrian authorities (BMK, Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology) would have used for approval. With this documentation the approval process for the installation of plate lines at an airport can be brought forward efficiently with relatively small adaptations to the requirements of the individual runway situation.

4.2.3 WP5 - EXE VLD-03-004 Detailed Demonstration Objectives Results

4.2.3.1 OBJ-VLD-03-004-001 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-001	Potential for increased runway capacity, with at least 5%, with	The capacity can be improved by 12,5% with the introduction of IRSF	OK

Criterion ID	Success Criterion	Validation Result	Status
	the introduction of the Integrated Runway Sequence Function has been demonstrated		

Stockholm-Arlanda Airport can, in the reference scenario, handle around forty arrivals per hour while also being allowed to land five aircraft per hour on the departure runway. This is based on the environmental permit that is active on Stockholm-Arlanda Airport at the time of the demonstrations, when runway configuration with parallel runways used in segregated mode. However, without a tool that allows early planning of sequence it can be hard to get the five landing on the departure runway to fit within the departure sequence. The IRSF, when used in Semi-automatic mode or Automatic mode, will either propose or plan the five landings on the departure runway, thereby optimizing the use of gaps at all times and increase the capacity from forty to forty-five landings per hour. This result in a calculated capacity increase of 12,5%. The results from the V3 validation shows an average runway capacity increase of 5.1%.

IRSF will also optimize sequence in regards to the turbulence category, for example landing heavy flights after another heavy flights in order to minimize and optimize gaps.

The following two statements could further improve the runway capacity:

- If the environmental permit was to be changed so that unlimited number of flights was allowed to land on the departure runway and take-off on the arrival runway, it would allow a free mixed mode operation to be used. This means that IRSF could be able to freely mix arrivals and departures between the different runways, thereby increasing runway capacity.
- The VLD demonstrations was based on live data in order to show how the system would work with real life traffic. However, IRSF are developed to handle more traffic than the amount that was used from live data, thereby the runway capacity can increase to allocate a higher number of flights.

4.2.3.2 OBJ-VLD-03-004-002 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-002	Potential for decreased departure taxi time with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data for taxi-time improvements has been gathered.	NOK Not available in the technical set-up

The results from the PJ02-08 V3 validation shows slightly longer taxi times compared to the reference scenario, mainly due to problem in departing heavy traffic in their intended gaps. Further development has been done to IRSF and it now allow the user to adjust the traffic situations between peak and off-peak traffic which adjust the departure queue at the runway hold. IRSF will calculate the needed gap between aircrafts for taxi, thereby minimizing the need for long taxi times with holdings and reducing the number of simultaneous taxiing departures. This will also make sure that heavy flights has a big enough taxi gap, making it easier to depart heavy flights.

The time it takes for a flight to taxi from a certain gate to a certain runway has been measured during longer periods of times, thereby ensuring that the gaps used in IRSF are as realistic as possible. The taxi times and gaps are also altered with respect to visibility value, based on how the visibility at the airport is and based on how the surface conditions of the taxiways and runways are at the airport.

All parameters mentioned can be changed in order to further improve and fine tune taxi times and gaps if needed.

No data from the VLD demonstration with focus on taxi times could be gathered. This due to uncertainties regarding taxi time as no ground radar was used during demonstration.

4.2.3.3 OBJ-VLD-03-004-003 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-003	Potential for decreased arrival flying time, in relation with capacity increase, with the introduction of the Integrated Runway Sequence Function has been demonstrated	Potential to decrease arrival flying time while also increasing runway capacity with the use of IRSF has been demonstrated.	OK

IRSF, when used in Semi-automatic mode or Automatic mode, will either propose or plan five landings on the departure runway. This will lead to a decrease in overall arrival flying time while also increase runway capacity.

With the improved planning from IRSF it will be easier for ATCOs to use RNP AR STAR as these shorter approaches often lowers the arrival flying time and increase the runway capacity.

If the environmental permit was to be changed so that unlimited number of flights was allowed to land on the departure runway and also perform departures on the arrival runway, it would allow a free mixed mode operation to be used. This means that IRSF could be able to freely mix arrivals and departures between the different runways, thereby planning the arrival to the closest runway instead of having to place flights in the queue to a certain arrival runway. This would also both decrease the arrival flying time and increase the runway capacity.

Observations from the demonstration shows that the arrival flying time could be decrease with help from IRSF.

4.2.3.4 OBJ-VLD-03-004-004 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-004	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated	The potential to avoid noise sensitive areas has been demonstrated by replanning of arrival flights to land on departing runway or using RNP AR, thereby lowering the noise over noise sensitive areas.	OK

As IRFS improve sequencing and planning on arrival flights, heavier flights can be placed to land on departure runway in order to avoid noise sensitive areas.

An example of this is when 01L is used as departing runway and 01R is used as arrival runway. Arrival flights will fly over a noise sensitive area when landing on 01R. By landing flights on 01L, that is the departing runway, the amount of noise produced over the noise sensitive area can be lowered.

Another example for minimizing the effect on noise sensitive areas are when RNP AR is being used for 01R. This makes the arriving flights to not approach Stockholm-Arlanda Airport over the noise sensitive areas. Thereby minimizing once again the produced noise over the noise sensitive area.

Both these examples need early planning of the sequence in order to be achieved in a safe way.

4.2.3.5 OBJ-VLD-03-004-005 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-005	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data regarding predictability and punctuality was gathered with focus on difference in actual and Flight Plan or RBT durations as Flight Plans was not updated with information from the solution. Thereby no reduction in variance of difference in actual and Flight Plan or RBT durations can be presented. Predictability and punctuality were observed to be improved by the system when observations on ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.	NOK Not available in the technical set-up

Results from the PJ02-08 V3 validation shows an average decrease of variation between actual and Flight Plan or RBT duration of 60.8%, thereby improving predictability, similar observations were done during the demonstration for flights that was monitored with IRSF but not altered.

For flights that was altered by IRSF, as the demonstration was done with live-data, the variance between flight plan and actual arrival time during the demonstrations could not be seen as real result. This is based on that IRSF often lowered the arrival flight time, thereby making the variance between actual landing time and flight plan higher while lowering fuel burn, CO2 emissions and arrival flight time. The reason for the difference between the result in the V3 validation and the demonstration is that during the V3 validation IRSF was used with pre-defined scenarios and the ATCO interacted with the system thereby making all the system connected and the flight plan was thereby impacted by IRSF.

During the VLD demonstration IRSF only used live-data that was not processed by the operational controllers, making the variance bigger when lowering flight times as real flight operations could not be affected. It is important to notice that predictability and punctuality was observed to be improved by the system when observations on additional ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.

4.3 Confidence in Results of Demonstration Exercises

4.3.1 Limitations and impact on the level of Significance

4.3.1.1 Quality of Demonstration Exercises Results

This has been elaborated on per exercise.

4.3.1.1.1 WP2-EXE-VLD-03-001C

Due to the limitations as described in Sections A.2 and A.3.4.1, the results from EXE-VLD-03-001C exercise must be caveated with such limitations. However, the results derived from the demonstration can still be considered of high value due to the following reasons:

- Experienced NATS Heathrow Approach controllers were used who have all had some previous involvement during the concept development stage of the Pairwise project.
- Although there were issues with the ExCDS tool with lag and crashing, the other aspects of the functionality with regards to conducting operational scenarios were working as designed and the controllers were given adequate exposure to the use of indicators for all aircraft pairs, using time-based PWS-RECAT-EU, Pairwise procedures and 2NM MRS on final approach. The controllers feedback indicated overall acceptability of the concept and tools, and would be comfortable for the tool to be implemented into Heathrow operations.

4.3.1.1.2 WP3-EXE-VLD-03-002

The analysis of the reduction of wake vortex lifetime and circulation strength by the installation of plate lines provides a clear picture of the benefits with respect to safety gains. However, in order to develop a safety case for reducing aircraft separations more detailed knowledge is needed. So, the

limited number of processed measurements in the individual lidar planes didn't allow to derive direct conclusive results regarding the efficiency of the plate effects depending on the distance to the plate lines and the flight height. However, a refined analysis with the P2P wake vortex model allowed to derive a propagation speed of the plate disturbances allowing conclusions on the plate line coverage. Also, at Vienna airport the number of landings of different heavy aircraft types is limited such that only aircraft specific results for the B763 and the B772 aircraft could be derived. A safety case for reduced separations enabled by plate lines may require data of more heavy aircraft types. For the consideration of the effects of reduced separations out-of-ground effect along the glide path, further OGE separation analysis may be needed for a safety case that will make this separation reduction potential available at congested airports.

The technical plate design was conducted very systematically with an intense exchange with experts leading to excellent results. A prototype plate has been installed near Vienna airport and another one will be installed on DLR premises in Oberpfaffenhofen. Further, the documentation needed for authority approval for the installation of plate lines at an airport location has been produced such that the installation of plate lines at an airport can be brought forward efficiently.

4.3.1.1.3 WP5-EXE-VLD-03-004

The results from the demonstrations are based on questionnaires, debriefings, expert judgement and observation of system performance when using presentation of live traffic and also of recorded traffic. The data collection and analysis are seen to be of high quality based on data received through good questionnaires and observations of the system.

4.3.1.2 Significance of Demonstration Exercises Results

This has been elaborated on per exercise.

4.3.1.2.1 WP2-EXE-VLD-03-001C

Although the planned experimental design was to control all variables between matched runs, in some instances, the controller was not the same in all positions, due to operational resourcing constraints. Therefore, any comparative assessment results should be caveated as such. Due to this reason as well as the limited number of matched runs conducted (6 x Matched Pairs), there cannot be any statistical significance attributed to the results, and rather should be used as indicative results only.

4.3.1.2.2 WP3-EXE-VLD-03-002

The statistical significance of the reduction of wake vortex lifetime has been tested with the Wilcoxon rank-sum test achieving very high confidences also for the different investigated aircraft types (A320 family, B763, B772). On the other hand, the number of measurements appeared too small to analyse plate effects in individual lidar measurement planes.

Operational significance is good as the investigations are based on Vienna International Airport which is one of the bigger airports and also reports low-level wake vortex encounters. On the other hand, the number of aircraft types of the category heavy may be too small for a safety case with reduced separations enabled by plate lines. The RECAT-EU scheme or the RECAT-EU-PWS (PairWise Separation) scheme together with the installation of plate lines may advance both, runway throughput for arrivals and safety in terms of the wake vortex encounter risks in the near term.

4.3.1.2.3 WP5-EXE-VLD-03-004

Observations has been performed on different flights on different days and information was gathered from persons with different work tasks and different views of the solution. Thereby has the risk for false results been minimised.

The SESAR large scale demonstration confirmed the ability to increase runway throughput by early and enhanced planning of an integrated runway sequence, applicable both in single runway operations, dependent runways and when using the two parallel runways in mixed mode.

According to the environmental permit for Stockholm-Arlanda Airport, up to five additional arrival flights per hour can land on the runway mainly used for departures (when runway configuration is set to use the parallel runways in segregated mode).

5 Conclusions and recommendations

5.1 Conclusions

5.1.1 WP2 - Optimised wake separation for arrivals with MRS and enhanced ROT - Exercise - EXE-VLD-03-001C

The following conclusions can be provided in relation to the Heathrow Pairwise concept:

- The pairwise concept is acceptable to controllers across operational configurations, including different runway configurations and wind conditions;
- Across a range of operational contexts, controllers found HMI and indicator support acceptable. Controllers generally found the system and HMI intuitive and understood system behaviours;
- The reduction of MRS on final approach from 2.5NM to 2NM, and an earlier reduction from 3NM to 2.5NM in the RMA is assessed as acceptable. All responses from controllers were positive, with participants agreeing this support is acceptable for operations;
- All participants agreed that the defined procedures are acceptable, as defined in the MOPs. Comments from controllers suggest that the alignment of new procedures with those pre-established in eTBS operations increases their acceptability;
- The Pairwise concept is acceptable to controllers in cases of broken off approaches, speed non-conformance and missing wake category scenarios;
- Controllers agreed that Early Line Zero is acceptable. The ELZ is seen as a benefit to the operation and useful as information to support the controller which improves predictability;
- The Pairwise concept supports an increase in arrival throughput in the Heathrow environment. This benefit is heavily influenced by the wind conditions and the individual controller's delivery relative to the displayed indicator. Larger data sets are required to provide a full understanding of the long-term capacity benefits;
- For the same traffic sequence, fuel and CO₂ savings can be expected with the implementation of the Heathrow Pairwise concept;
- The updated MRS rules decrease the proportion of MRS constrained aircraft pairs at threshold in the traffic sequence. MRS pairs are only present under Pairwise operations in strong wind conditions, where the wake and ROT constraints are reduced;
- From a Human Performance perspective, the overall conclusion drawn from the evidence gathered is that the concept is feasible but requires further refinements being made to some components of the ATM system (i.e., technology, system design and people) and reassessing the impact on HP to improve confidence that the results are accurate and reliable.
- The overall findings of the safety assessment are positive, with no major safety issues having been identified. Furthermore, all Demonstration Success Criteria relating to Safety have been met.

5.1.2 WP3 - Wake decay plate lines - Exercise - EXE-VLD3-002

The analysis of over 1000 wake vortex evolutions measured at Vienna airport indicates that the plate lines reduce the lifetimes of the vortices in a safety corridor along the final approach in ground proximity by 22–37% depending on the aircraft type. This corresponds to a reduction of vortex

circulation by about 50% for the most relevant ICAO separation (Medium behind Heavy). Even though plate lines are only effective close to the ground, they still support a potential reduction of the separation further up on the glideslope. When using RECAT-EU as reference, substantial benefits can only be gained for some – albeit relevant – aircraft category combinations. When using RECAT-EU-PWS as reference, for most aircraft pairings, benefits of about 0.5 NM (15%) separation reduction seem to be possible when using plate lines. In the near term the RECAT-EU scheme or the RECAT-EU-PWS scheme together with the installation of plate lines may advance both simultaneously, runway throughput for arrivals and safety in terms of the wake vortex encounter risks. The technical plate design was developed very systematically from 15 initial draft designs in an intense exchange with experts leading to a design which is now ready for installation at busy airports. This includes the documentation needed for the required authority approval. A prototype plate has been installed near Vienna airport and another one will be installed on DLR premises in Oberpfaffenhofen.

5.1.3 WP5 - Integrated Runway Sequencer Function Exercise (EXE-VLD-03-004)

The Integrated Runway Sequence Function (IRSF) has, during the long demonstration periods, worked without any problems or crashes, this indicates that the system is stable and can handle live-data during longer periods of time. The demonstrations proved that the solution and the system still reach the earlier validated results from the V3 real time simulation. KPAs such as **capacity**, **efficiency**, **predictability** and **safety** has also been demonstrated with positive results, showing that there are benefits to be made for the airports that choose to use a system based on IRSF.

5.2 Recommendations

5.2.1 Recommendations for industrialisation and deployment

5.2.1.1 WP2

- The ‘pulling away’ phenomenon experienced by participants where the indicator moved ahead of the aircraft once its speed had been stabilised is recommended to be investigated to confirm whether this was prompted by the simulation performance within 4DME not being consistent with operational data or in fact a tool calibration issue.
- The participant suggestion to avoid 2.5 MRS losses by introducing a standardised drop to a higher altitude than used in the current operation to give the final approach controller the option to use vertical separation should be explored by the concept team to determine the potential inclusion of this procedure in the ConOps.
- The functionality of the Status Spacing Window interface is recommended to be reviewed prior to the final validation of the concept to ensure that the presented information reliably gains the controller’s attention, when needed.
- Tool behaviour in any unusual/edge-case scenarios are highlighted in controller training and in the ConOps.
- The next phase of development should review the relevance of the spacing information displayed for dependant aircraft pairs and of the indicator HMI and display for aircraft outside 20 miles from the threshold.
- Conduct further validation and tool verification activities on the final deployment IA and ExCDS software builds, including final deployment adaptation, to ensure thorough user validation is conducted with all aspects of the functionality working as designed.

- The scale of the final validation activities should be such that a greater number of matched runs in each combination of wind sample and traffic mix can be performed. A larger data set would add further confidence to the performance benefit findings.
- For the formal validation simulations conduct a review of aircraft speed performance modelling inside 4DME in the simulator is to ensure that it is consistent with operational data.
- Conduct validation with users who have not been involved in the development of the concept prior, to ensure a balanced view is obtained.
- Ensure a list of scenarios (particularly all edge case scenarios for IA tool behaviour) that are required to be covered and highlighted in ATC training is compiled.
- Additional HP assessment is recommended to correct for unrealistic ExCDS input/non-ATCO matches.
- The next phase of development should further investigate the validity of the perception that the HMI design of the tools and the operating techniques/procedures associated with the tools increase controllers' workload and whether than increase is acceptable (i.e. falls within the normal variability of workload levels).
- The next phase of development should assess the validity of the perception that more than 0.5nm would be safer for breakthrough.
- The next phase of development should also collect HP data from ATCOs without previous knowledge of or interaction with the concept tools
- SESAR should consider investigating the effectiveness of humans as fallbacks when technology systems fail.

5.2.1.2 WP3

A number of European airports and the respective ANSPs have been approached to conduct an exchange with respect to the airports' needs regarding wake vortex risks and runway capacity. The goal was to find out whether the airports and ANSPs are interested to install plate lines, on which facts such a decision is based and what further development is needed to make plate line installation an attractive asset.

It became clear that mere safety gains consisting of a reduction of wake vortex encounters in ground proximity and resulting go-arounds do not yet justify an investment in the installation of a plate line as the current situation is considered sufficiently safe. However, for congested airports it would be attractive to install a plate line if the landing capacity could be increased. Five use cases were established which need to be further developed.

- Use Case I. Reduced wake-vortex lifetime will reduce encounter frequency corresponding to an improved safety performance. The reduced encounter frequency will reduce the go-around rates, leading to positive impacts on fuel efficiency, resilience and capacity.
- Use Case II. The introduction of the RECAT-EU scheme or the RECAT-EU-PWS (PairWise Separation) scheme together with the installation of plate lines may advance both, runway throughput for arrivals (three or five additional landings per hour during peak demand) and safety in terms of the wake vortex encounter risks. The PWS scheme requires the installation of some controller support like the separation delivery tool LORD (Landing with Optimum Runway Delivery) developed by EUROCONTROL.
- Use Case III. On top of use case II, additional capacity gains of up to two additional landings per hour during peak demand can be made accessible by translating accelerated wake vortex decay into reduced separations following the methods developed for RECAT-EU and RECAT-EU-PWS. As the plates reduce wake vortex lifetime only in ground proximity, it is

required to demonstrate that the aircraft separations are still safe along the glide slope. The determined minimum separations along the glide slope reduce the expected capacity gains mainly for RECAT-EU while for RECAT-EU-PWS only a few leading aircraft types restrict some of the aircraft combinations.

Use Case IV. The application range of the REDSEP method developed for airport Vienna may be extended to situations with weak winds. REDSEP can also be applied at other airports.

Use Case V. On top of use cases I to IV, aircraft separation may be reduced tactically depending on the prevailing weather conditions and the resulting wake vortex behaviour. The delivery of pairwise dynamic separations (RECAT III) requires monitoring and prediction of weather conditions along the glide path. The conducted analysis shows that plate lines reduce the longest-lived wake vortices in ground proximity that are not blown out of the glide path corridor by crosswinds with a strength below 2 m/s. As such reasonable worst-case conditions occur only in about 2% of the time, the corresponding separation gains for pairwise dynamic separations by plate lines are also quite limited and amount to about 2%.

5.2.1.3 WP5

Knowledge from V3 validations and VLD can be used as requirements for further development in order to industrialize and deploy the solution. See chapter A.5.1 for details.

5.2.2 Recommendations on regulation and standardisation initiatives

5.2.2.1 WP2

NATS will be engaging with the UK CAA to obtain the required regulatory assurance to deploy all related updates to separation standards into Heathrow operations. There are no recommendations to include at this stage.

5.2.2.2 WP3

In order to develop a safety case for one of the use cases III to V it would be needed to provide measurements for more heavy vortex generators and to clearly show which area of the final approach is sufficiently covered by the beneficial plate line effects.

5.2.2.3 WP5

The processes for handling a new system based on IRSF will be the same as the airport CDM procedures already in use. No further change to regulations and standardisation is seen as required.

5.2.3 Recommendations for updating ATM Master Plan Level 2

For WP3, the Plate Lines concept needs to be further developed to increase capacity (runway throughput) at airports and increase safety. Required are concepts for the combination of the Plate Lines with the separation schemes RECAT-EU, RECAT-EU-PWS, Dynamic Pairwise Separations (D-PWS, RECAT III) and REDSEP and potentially MRS 2.0 (Minimum Radar Separation 2.0) and the accomplishment of convincing estimates of runway throughput and safety gains enabled by Plate Lines including the respective safety arguments needed for authority approval in order to facilitate the installation of Plate Lines at airports.

The WP2 and WP5 exercise outcomes did not require any update of the Master Plan.

6 Summary of Communications and Dissemination activities

6.1 Summary of communications and dissemination activities

Please refer to the Communication, Dissemination and Exploitation Plan of this project for a full overview [19]. A few main highlights per WP (or Demo event) were:

WP1 (Management):

The project's website was set up, hosted by SJU, and several LinkedIn communication posts were provided about the SESAR Innovation Days, Open Days of DLR and ACG (under WP3) and of LFV, SINTEF and SWEDAVIA (under WP5). These days were also actively supported by the coordinator NLR (AT-One)

WP2:

A number of LinkedIn posts featured the Intelligent Approach Pairwise solution, including a communication highlighting a recent Queue Management Forum which focussed on the PWS Development Sims. WP2 Pairwise, ROT and MRS work featured in the SID poster showcasing the project's work for the SESAR Innovation Days (SIDs) 2021 and a summary paper and poster were submitted and presented at the SIDs in December 2022. During Airspace World in 2023, VLD3 WP2 was presented at the SESAR Showcase Theatre and formed part of a SESAR Walking Tour to promote NATS' work in operation. Finally, the concept was also included on a poster presentation at the PJ.02-W2 Final Event in March 2023. In addition to this, NATS communications were shared on our internal social media highlighting both the PWS development simulations and the actual final demonstration simulations.

An online Open Day is being planned for May 2023 where details of the integrated solutions will be shared and information given on the demonstration activity itself. This will be followed by an article to be written on the external NATS website.

WP3:

Several project LinkedIn posts and teasers on the homepage of the DLR Institute of Atmospheric Physics have documented the progress after meaningful achievements. The achieved results have been presented on five international scientific Conferences (talks, partly invited and one poster presentation) and published in three respective scientific conference proceedings. Three manuscripts have been published in renowned peer reviewed scientific Journals. Further, the results were presented in the SESAR Digital Academy Webinar, at the SESAR Innovation Days and at the SESAR Annual Conference in 2022. A hands-on experiment, a plate exhibit together with an automatic presentation were shown at the World ATM Congress in Madrid in June 2022 at the AT-ONE booth where also a flyer and a white paper were distributed among interested visitors. The visitor day took

place on 14 February 2023 at the tower of Vienna airport where several presentations were given and the plate prototype installed at Rauchenwarth was visited. More than 20 international visitors attended the event in person while another 20 colleagues watched the presentations online. The presentations were recorded and made available after the visitor day. In the framework of a Helmholtz field study fellowship interviews were conducted with several European airports, ANSPs and airlines to better understand their needs and interests and market opportunities connected to the plate line methodology

WP5:

A number of activities has been performed to present the results of IRSF demonstrations;

- Open day in Malmö the 9th June 2022 with visitors from a large number of organisations.
- Development of a video describing the VLD-03-004 demonstration of IRSF for Stockholm-Arlanda, including feedback from actors in the project (LFV, Swedavia and SINTEF).
- Development of a scientific paper to describe Integrated Runway Sequence Management (IRSM) and benefits for Stockholm-Arlanda Airport. This paper has been distributed to stakeholders.
- Presentation of IRSM at SESAR Innovation Days in Budapest 6 to 8 December 2022.

6.2 Target Audience Identification

6.2.1 WP2

Target audience for WP2 are primarily major airports and their ANSPs as well as airlines.

6.2.2 WP3

Target audience for WP3 are primarily major airports and their ANSPs as well as airlines.

6.2.3 WP5

Target audience for the VLD-03-004 demonstrations are, TWR ATCOs, APP ATCOs, En-route ATCOs, Watch Supervisors, ATCC Management, ATC Experts, chief of operations, Swedavia operational units, Stand Management, Field operations, AUs, LFV HQ personnel, Swedish CAA, Swedavia Management and Airspace Users.

6.3 Project High Level Messages

Please refer to the Communication, Dissemination and Exploitation Plan of this project for the main project messages [19].

7 References

Content Integration

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- [4] OFA 01.03.01 Enhanced Runway Throughput Consolidated Final Step 1 OSED, P06.08.01 D30, Edition 00.01.00, 31st May 2016.
- [5] SESAR VLD3-W2-SORT D1.1 DEMO Plan – Part I, Edition 00.03.00 (issued as D1.1.04), 10 February 2023.

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Safety

- [11] SESAR Joint Undertaking, 10436 – Safety Guidance Reference Material (SRM), 2018.
- [12] EUROCONTROL, RECAT-EU, European Wake Turbulence Categorisation and Separation Minima on Approach and Departure, Edition 1.2, 14/02/2018.
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- [14] EUROCONTROL, European Proposal for revised Wake Turbulence Categorisation and Separation Minima on Approach and Departure, “RECAT – EU”, Safety Case Report.

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[18] N/A

Communication and dissemination

[19] SESAR 2020 VLD3-W2-SORT D1.1.03 Communication, Dissemination and Exploitation Plan, Edition 00.02.03, 31 January 2023. Latest Edition Available at STELLAR.

Programme management

For what concerns the general collaboration between all the members of the programme:

[20] SESAR3 Membership Agreement, 2016.

[21] SESAR3 Programme Management Plan. Ed. 01.00.00, 23/11/2017.

For what concerns the definition of the solutions being addressed by the project, their initial maturity levels and the target maturity dates aimed for:

[22] SESAR Joint Undertaking ATM Master Plan-Executive view, 2020 Edition.

[23] SESAR Joint Undertaking Maturity Report 2021, Ed. 01.00.00, 30/09/2021.

[24] SESAR Joint Undertaking Extended Release Strategy, Ed 06.00.00, 09/06/2022.

[25] Single Programming Document 2019-2021, SJU, 12/12/2018.

For what concerns the specific scope of work covered by this project and the general way of working expected from all projects in the SESAR3 programme:

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[27] SESAR3 Project Handbook, Project Execution Guidance, 2020.

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- [33] F. Holzäpfel, L. Strauss, C. Schwarz, Assessment of Dynamic Pairwise Wake Vortex Separations for Approach and Landing at Vienna Airport, Aerospace Science and Technology, Vol. 112, May 2021, Article 106618, <https://doi.org/10.1016/j.ast.2021.106618>.
- [34] G. Rotshteyn, F. Holzäpfel, Plate Lines: Technical Design, VLD3-W2-SORT, D3.1.02 / PMP.006, Edition 00.01.00, 09 April 2021, 26 pages.
- [35] G. Rotshteyn, F. Holzäpfel, Complete Documentation Required for Approval of National Authorities on WP3 Platform Use, VLD3-W2-SORT, Milestone M5 Report, Edition 00.01.00, 22 August 2022, 16 pages.
- [36] Pawel Gruszkiewicz, Gutachten zu dem Projekt SESAR2020 Wirbelschleppen Messkampagne am Flughafen Wien, Wien, 10 June 2022, 38 pages.
- [37] Pawel Gruszkiewicz, Bestätigung zur Umsetzung der gutachterlichen Empfehlungen zu dem Projekt SESAR2020 Wirbelschleppen Messkampagne am Flughafen Wien – Plate Lines, Wien, 2 September 2022, 5 pages.

7.1 Reference Documents

The following documents were used to provide input / guidance / further information / other:

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- [45] D1.4 - SESAR 2020 VLD3 SORT DEMO Report - Part V Performance Assessment Report (PAR).

Appendix A Demonstration Exercise EXE VLD-03-001C Report

A.1 Summary of the Demonstration Exercise EXE-VLD-03-001C Plan

A.1.1 Exercise description and scope

WP02 - Optimised wake separation for arrivals with MRS and enhanced ROT concepts – Real Time Simulation for Heathrow Approach.

The SESAR solutions under the scope of this exercise are:

- **PJ.02-01-01 (AO-0328): Optimised Runway Delivery (ORD) on Final Approach**
- **PJ.02-01-04 (AO-0306): Wake Turbulence Separations (for Arrivals) based on Static Aircraft Characteristics**
- **PJ.02-03 (AO-0309): Minimum-Pair Separations based upon Required Surveillance Performance (RSP)**
- **PJ.02-08-03 (AO-0337): Reduced separation based on local Runway Occupancy Time characterisation**

Solution #64 (TBS) is part of the baseline.

This information is taken from EATMA Version DS23-draft.

Operational Scope in terms of actors and processes

The operational scope of this demonstration is to utilise the Intelligent Approach (IA) Platform in a simulator of Heathrow approach, using the Separation and Spacing Indicators generated to position aircraft against.

Valid Heathrow Approach controllers participated in all exercises and followed procedures defined for the solution concept.

The national regulator will have visibility of the simulation activity as part of the validation and assurance evidence ahead of full operational deployment.

Reference scenario

The reference scenario consists of simulation runs using the current eTBS tool with RECAT-EU Wake Separation scheme. This served as a control against which the results of the solution scenario could be compared and measured against.

Solution scenario

The solution scenario used an early operational version of the IA Platform which provides indicators to position aircraft against, with a reduced separation minimum on final approach and providing improved predictions of runway occupancy time according to aircraft type. This involves the use of new operating procedures for the Core ATC team involved in the trial.

The Pairwise system also provides an early indication of the required separation or spacing, which is displayed in Early Line Zero (ELZ) on the aircraft track data block on the radar display.

Demonstration technique and platform used.

The demonstration technique used a real time simulation of Heathrow Final Approach utilising the solution platform. Traffic samples were used that represent the change in aircraft fleet make up since the Covid 19 Pandemic and based on a future 2027 schedule at Heathrow Airport.

Identical traffic samples together with specific wind conditions were used with both the reference and solution scenarios to allow direct comparison on the improvements enabled by use of the solution platform.

A.1.2 Summary of Demonstration Exercise EXE-VLD-03-001C Objectives and success criteria

Demonstration Objective	Demonstration Success criteria	Coverage and comments on the coverage of Demonstration objectives	Demonstration Exercise Objectives	Demonstration Exercise Success criteria
OBJ-VLD-03-001C-ACC	CRT-VLD-03-001C-ACC-001	Full Coverage	EXE-OBJ-VLD-03-001C-ACC To assess the acceptability of reduced MRS and PWS TBS	EXE-CRT-VLD-03-001C-ACC-001 The combined solution is found to be acceptable to controllers under all runway operating configurations demonstrated
	CRT-VLD-03-001C-ACC-002			EXE-CRT-VLD-03-001C-ACC-002 The combined solution is found to be acceptable to controllers under all wind conditions demonstrated
	CRT-VLD-03-001C-ACC-003			EXE-CRT-VLD-03-001C-ACC-003 The combined solution is found to be acceptable to controllers when managing aircraft pairs with ROT or Spacing as the maximum constraint
	CRT-VLD-03-001C-ACC-004			EXE-CRT-VLD-03-001C-ACC-004 The combined solution is found to be acceptable to controllers when managing aircraft pairs with Wake as the maximum constraint

	CRT-VLD-03-001C-ACC-005			EXE-CRT-VLD-03-001C-ACC-005 The combined solution is found to be acceptable to controllers when managing scenarios where a wake breakthrough indicator is present
	CRT-VLD-03-001C-ACC-006			EXE-CRT-VLD-03-001C-ACC-006 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing LVPs (Low Visibility Procedures)
	CRT-VLD-03-001C-ACC-007			EXE-CRT-VLD-03-001C-ACC-007 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing VIS2 (Visibility Condition 2)
	CRT-VLD-03-001C-ACC-008			EXE-CRT-VLD-03-001C-ACC-008 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing runway inspections
	CRT-VLD-03-001C-ACC-009			EXE-CRT-VLD-03-001C-ACC-009 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing EMT (Early Morning TEAM)
	CRT-VLD-03-001C-ACC-010			EXE-CRT-VLD-03-001C-ACC-010 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing departure gaps during EMT
	CRT-VLD-03-001C-ACC-011			EXE-CRT-VLD-03-001C-ACC-011 The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing tactical spacing gaps
	CRT-VLD-03-001C-ACC-012			EXE-CRT-VLD-03-001C-ACC-012 The combined solution is found to be acceptable to controllers in missed or broken off approach scenarios
	CRT-VLD-03-001C-ACC-013			EXE-CRT-VLD-03-001C-ACC-013 The combined solution is found to be acceptable to controllers in aircraft speed non-conformance scenarios
	CRT-VLD-03-001C-ACC-014			EXE-CRT-VLD-03-001C-ACC-014 The combined solution is found to be acceptable to controllers in missing aircraft wake category information scenarios
	CRT-VLD-03-001C-ACC-015			EXE-CRT-VLD-03-001C-ACC-015 The generation and display of the Early Line Zero to support the Base Leg turn is found to be acceptable to controllers
OBJ-VLD-03-001C-EFF	CRT-VLD-03-001C-EFF-001	Full Coverage	EXE-OBJ-VLD-03-001C-EFF	EXE-CRT-VLD-03-001C-EFF-001 The average arrival movement rate increases when compared to the reference scenario

	CRT-VLD-03-001C-EFF-002		To assess the impact of reduced MRS and PWS TBS on operational efficiency	EXE-CRT-VLD-03-001C-EFF-002 The number of aircraft pairs that have minimum radar separation as their maximum constraint decreases when compared to the reference scenario
	CRT-VLD-03-001C-EFF-003			EXE-CRT-VLD-03-001C-EFF-003 The effectiveness of the delivery of aircraft to the separation minima at the base leg stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-004			EXE-CRT-VLD-03-001C-EFF-004 The effectiveness of the delivery of aircraft to the separation minima at the intercept stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-005			EXE-CRT-VLD-03-001C-EFF-005 The effectiveness of the delivery of aircraft to the separation minima at the final approach stage is shown to be acceptable
	CRT-VLD-03-001C-EFF-006			EXE-CRT-VLD-03-001C-EFF-006 The delivery conformance to the displayed indicators on the final approach is shown to be acceptable
OBJ-VLD-03-001C-ENV	CRT-VLD-03-001C-ENV-001	Full Coverage	EXE-OBJ-VLD-03-001C-ENV To assess the impact of reduced MRS and PWS TBS on environmental efficiency	EXE-CRT-VLD-03-001C-ENV-001 Average CO2 emissions per flight are reduced when compared to the reference scenario
OBJ-VLD-03-001C-HP	CRT-VLD-03-001C-HP-001	Full Coverage	To assess the impact of reduced MRS and PWS TBS on human performance	EXE-CRT-VLD-03-001C-HP-001 Controller workload is shown to remain within acceptable levels
	CRT-VLD-03-001C-HP-002			EXE-CRT-VLD-03-001C-HP-002 Situational Awareness is shown to remain at the same level or is improved
	CRT-VLD-03-001C-HP-003			EXE-CRT-VLD-03-001C-HP-003 The likelihood and consequence of human error are assessed as remaining within acceptable levels
	CRT-VLD-03-001C-HP-004			EXE-CRT-VLD-03-001C-HP-004 The procedures are found to be acceptable by controllers
	CRT-VLD-03-001C-HP-005			EXE-CRT-VLD-03-001C-HP-005 The Method of Operations are found to be acceptable by controllers
	CRT-VLD-03-001C-HP-006			EXE-CRT-VLD-03-001C-HP-006

				The teamwork and communication enabled are shown to be acceptable EXE-CRT-VLD-03-001C-HP-007 User roles and responsibilities are shown to remain acceptable EXE-CRT-VLD-03-001C-HP-008 User Confidence is shown to remain within acceptable limits EXE-CRT-VLD-03-001C-HP-009 The tool is shown to support the controllers in their decision making processes EXE-CRT-VLD-03-001C-HP-010 The tool is shown to provide sufficient, clear, accurate and timely information to the controller EXE-CRT-VLD-03-001C-HP-011 Controller trust in the integrity of the tool support and reliance on indicators are shown to be acceptable
OBJ-VLD-03-001C-SAF	CRT-VLD-03-001C-SAF-001	Full Coverage	EXE-OBJ-VLD-03-001C-SAF	EXE-CRT-VLD-03-001C-SAF-001
	CRT-VLD-03-001C-SAF-002			The number of missed approaches due to insufficient spacing is no greater than in currently operations EXE-CRT-VLD-03-001C-SAF-002 Interoperability evidence can be produced to confirm that the elements of all solutions when combined do not degrade the level of safety. EXE-CRT-VLD-03-001C-SAF-003 The combined solution and procedures cause no losses of separation in the demonstration exercise EXE-CRT-VLD-03-001C-SAF-004 The combined solution and procedures cause no increase in the frequency of go arounds when compared to the reference scenario
	CRT-VLD-03-001C-SAF-003			
	CRT-VLD-03-001C-SAF-004			
OBJ-VLD-03-001C-SEC	CRT-VLD-03-001C-SEC-001	Full Coverage	EXE-OBJ-VLD-03-001C-SEC	EXE-CRT-VLD-03-001C-SEC-001
	CRT-VLD-03-001C-SEC-002			A Security Risk Assessment is carried out EXE-CRT-VLD-03-001C-SEC-002 Security Risk Treatments are applied

Table 12: Demonstration Objectives applicable to Exercise VLD-03-001C

A.1.3 Summary of Demonstration Exercise EXE-VLD-03-001C Scenarios

The exercises listed within this section were used with both the Reference and Solution scenarios in order to provide results for comparison.

A.1.3.1 Reference Scenario

The reference scenario uses the London Terminal Control Simulator at NATS Whiteley.

The scenario replicates the operational layout of the Heathrow Approach in the London Terminal Control and is configured with the current operational systems used in the operation.

The system used in the reference scenario includes the existing eTBS system used in current operations on Heathrow Approach, which is configured with RECAT-EU wake turbulence categorisation and ORD support. This is supported by AMAN, which provides the flight and spacing information to TBS.

The airspace simulated is centred on the Heathrow Airport Radar Manoeuvring Area (RMA) with extension out to the BIG, LAM, OCK and BNN holds, used for Heathrow inbound traffic.

A number of traffic samples is used, simulating different aircraft fleet mixes, weather conditions and visibility conditions. Approaches to multiple runways are also simulated.

The Minimum Radar Separation is 3NM in the TMA and Approach environment with the exception of a reduction to 2.5NM MRS when the lead aircraft is established on the extended runway centreline from threshold. In addition, the reference scenario assumes the controllers are applying 3NM minimum spacing before 4DME.

A.1.3.2 Solution Scenario

The Solution scenario uses the London Terminal Control Simulator at NATS Whiteley.

The scenario replicates the operational layout of the Heathrow Approach in the London Terminal Control and is configured with the forthcoming Intelligent Approach (IA) Platform and an integration of the IA tool with the ExCDS Flight Strip system. This is referred to as the “Pairwise” solution.

The Intelligent Approach system used in the solution scenario incorporates the solution OIs covering Pairwise Wake Turbulence Categorisation, reduced Minimum Radar Separation to 2NM and improved ROT Management based upon NATS analysis of historical Runway Occupancy Times at Heathrow Airport.

The PWS system applies ROT values that are adaptable per landing runway for either the wake category, aircraft type or aircraft type + operator level. The ROT adaptation values are then calibrated using a modelling process to provide assurance that the pressure on the Tower AIR controller’s clearance to land instruction shall remain within acceptable bounds relative to the current day operation.

The modelling process takes account of the variability in delivery expected to be achieved. The ExCDS Flight Strip System provides the flight and spacing data source for Intelligent Approach.

The airspace simulated is identical to the reference scenario, centred on the Heathrow Airport Radar Manoeuvring Area (RMA) with extension out to the BIG, LAM, OCK and BNN holds, used for Heathrow inbound traffic.

The same traffic samples are used as in the reference scenario exercises which include different aircraft fleet mixes, weather conditions and visibility conditions. Approaches to multiple runways are simulated.

The Minimum Radar Separation in effect is the solution-specific 2.0NM MRS on final approach to runway threshold with an earlier reduction to 2.5NM MRS when the leader is on a stable intercept heading. Indicators are capped at no less than 2.5NM spacing before 4DME.

The data collection from the solution scenario exercises is used to measure against the reference scenario to calculate any impact on arrival runway throughput at the airport whilst using the IA Platform within the simulator, along with other KPAs such as Fuel Efficiency and Safety. Controller surveys and feedback are also used to compare against the reference scenario from a Concept, Human Performance and Safety point of view.

In addition to the comparison between the reference and solution scenario, the acceptability of the concept and associated procedures is assessed.

A.1.4 Summary of Demonstration Exercise EXE-VLD-03-001C Assumptions

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-001-001	2NM Minimum Radar Separation Approval	Regulatory	It is assumed that the approval of the 2NM MRS with the national regulator at a point after the demonstration does not necessitate any change to procedures from those demonstrated in the exercises.	The operational assurance for live operations has not been confirmed at the point of the demonstration.	None
ASS-VLD-03-001-002	National Lockdowns	Time planning	It is assumed that there will be no further national lockdowns that may impact the ability of NATS to hold the	Due to the impact of COVID and lockdowns, activity on operational sites was historically restricted.	A National Lockdown may restrict the ability for individuals to attend the

			demonstration activities.		facility and for rostering Controllers.
ASS-VLD-03-001-003	Applicability to Other Airports	Applicability of research results	It is assumed that the results from Heathrow Approach will be applicable to other airports of equivalent size and throughput.	The ROT characteristics and development have specifically focussed on Heathrow Airport which is the first operational deployment of the combined solution.	None

Table 17: EXE-VLD-03-001C Assumptions overview

A.2 Deviation from the planned activities

IA and ExCDS Functionality:

The solution runs were conducted using an early integration (pre-FAT) build of the IA and ExCDS software. During the integration and testing activities prior to the simulation delivery days, issues were identified with the ExCDS and IA software:

- ExCDS software server crash, which caused the controllers' ExCDS panels to freeze for ~4 minutes on each crash occasion during the run. These crashes impacted strip management and clearance entry. By extension, this affected the human performance of the controllers, who could not use the strip markings/position to support their situational awareness during these periods.
- ExCDS HMI lag, which was caused when the full Controller Working Position (CWP) configuration (3 x positions) were using ExCDS simultaneously. This tended to progressively worsen during the exercises, leading to an ExCDS crash.
- Intermittent display of 'Early Line Zero' values, which is the IA tool display (prior to the base-leg turn) of the spacing value to be applied behind the lead aircraft on final approach. With the Pairwise concept, if this information is missing, then the controller has to revert to using their judgement.

Controllers were requested to make minimal ExCDS inputs to mitigate this issue. This approach was adopted throughout the simulation, until the final delivery day when an updated ExCDS software build was delivered. This updated build resolved the issues and the controllers were able to use ExCDS as intended for the final two solution runs.

Due to the issues, the order of the planned activities for each simulation day was amended from the original plan. The original plan had been to conduct the matched exercises on the first two delivery days, allowing maximum time for data extraction and analysis for the comparative assessment, with the final two days being utilised to fully test all aspects of the Pairwise functionality through the generation of operational scenarios.

It was agreed prior to the delivery day commencement that leaving the matched runs until the end of the delivery days maximised the available time for the issues to be investigated and for a software fix to be delivered.

Even with the software fix, the majority of the Pairwise runs and therefore the data collected from these runs impacted the ability to adequately assess Human Performance measures such as workload and situational awareness. For example, as the controllers interacted far less with the flight strips under the solution run than they did in under reference conditions, there is likely to be an impact to the comparative human performance analysis. Therefore, the Human Performance results of this simulation must be heavily caveated with such limitations.

Comparative Experimental Design:

As described in Section A.1.1, in order to conduct a comparative assessment between the reference scenario and solution scenario, a matched experimental design was implemented, where the conditions across runs were kept constant in terms of traffic sample, wind conditions, and the controller in each position. The dependent variable in this case was the tool in use - either eTBS with RECAT-EU or Pairwise.

However, the matched runs were not executed exactly as planned. For some of the delivery days, the Controllers that had been named at the time of planning the experimental design were no longer available for the simulation when the Controller schedules were published, due to operational constraints. In addition, changing the scheduled dates on which the matched runs were conducted verses the scenario runs (as explained above) compromised the matching of the participant seating configuration. As a result, comparative results between matched runs may be subject to additional variability due to this factor.

Lastly, additional baseline runs were introduced to the timetable during the simulation. This was based on feedback from the controllers regarding the potential capacity differences between eTBS and Pairwise under various wind conditions. Therefore, a decision was made to run two additional baseline runs in strong and moderate wind conditions to enable a more representative assessment of the Capacity KPI. This impacted the ability to conduct a matched comparison for an Early Morning Team (EMT) run in both runway directions, however this was deemed acceptable as it is the segregated runs that are of most significance to this exercise.

A.3 Demonstration Exercise EXE-VLD-03-001C Results

A.3.1 Summary of Demonstration Exercise EXE-VLD-03-001C Results

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
EXE-OBJ-VLD-03-001C-ACC	To assess the acceptability of reduced MRS and PWS TBS	EXE-CRT-VLD-03-001C-ACC-001	The combined solution is found to be acceptable to controllers under all runway operating configurations demonstrated	Very Large and Large Airports, Segregated mode operations	Qualitative survey responses demonstrate that the pairwise concept is highly acceptable to controllers regardless of the runway in use.	OK
		EXE-CRT-VLD-03-001C-ACC-002	The combined solution is found to be acceptable to controllers under all wind conditions demonstrated	Very Large and Large Airports, Segregated mode operations	Qualitative survey responses showed that the pairwise concept is acceptable across all wind conditions demonstrated.	OK
		EXE-CRT-VLD-03-001C-ACC-003	The combined solution is found to be acceptable to controllers when managing aircraft pairs with ROT or Spacing as the maximum constraint	Very Large and Large Airports, Segregated mode operations	Qualitative survey responses showed that the pairwise concept is acceptable for managing aircraft pairs with ROT or spacing as the maximum constraint.	OK
		EXE-CRT-VLD-03-001C-ACC-004	The combined solution is found to be acceptable to controllers when	Very Large and Large Airports,	Qualitative survey responses showed that the pairwise concept is acceptable for managing	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
			managing aircraft pairs with Wake as the maximum constraint	Segregated mode operations	aircraft pairs with Wake as the maximum constraint.	
		EXE-CRT-VLD-03-001C-ACC-005	The combined solution is found to be acceptable to controllers when managing scenarios where a wake breakthrough indicator is present	Very Large and Large Airports, Segregated mode operations	Acceptability of the Wake Breakthrough indicator was generally accepted, as five controllers strongly agreed that HMI and indicator support was acceptable. However, one controller somewhat disagreed, arguing that 0.5NM can sometimes be insufficient for recovery and that 0.75NM could be more suitable. It should be noted that the Wake Breakthrough behaviour is the same in Pairwise as in eTBS today, however this is a value that is adaptable and therefore can be taken forward for consideration.	OK
		EXE-CRT-VLD-03-001C-ACC-006	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing LVPs (Low Visibility Procedures)	Very Large and Large Airports, Segregated mode operations	During the operational scenarios a transition from VIS1 to VIS2 to LVPs and reverting back again was simulated. During the debrief the controllers commented that they found the Indicator support to be acceptable. However, there were comments in the end of participation questionnaire that the information in the Status Spacing Window could stand out more and in addition, more exposure to these types of scenarios is required for familiarity of using the Spacing input functionality.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
		EXE-CRT-VLD-03-001C-ACC-007	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing VIS2 (Visibility Condition 2)	Very Large and Large Airports, Segregated mode operations	See above relating to EXE-CRT-VLD-03-001C-ACC-006.	OK
		EXE-CRT-VLD-03-001C-ACC-008	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing runway inspections	Very Large and Large Airports, Segregated mode operations	During Runway inspections, it was noted that in the majority of cases, the lead aircraft will land before the follower has turned base leg and therefore the ELZ or the indicator and LZ value will be lost (depending on the point of the follower aircraft). This was discussed during the debrief and all of the controllers felt this was not an issue, as they are able to remember the 4DME indicator value and 'round up', and if not, refer to the threshold value that is displayed on the designator. There was no concern regarding safety, due to the fact it is a spacing gap rather than a separation.	OK
		EXE-CRT-VLD-03-001C-ACC-009	The indicator support, HMI and associated procedures are found to be acceptable to controllers when	Very Large and Large Airports, Segregated mode operations	Dependant runway constrained aircraft showed high acceptability from controllers, but only three strongly agreed, while the other three rated this somewhat agree. One controller did not like the ELZ for dependent aircraft being displayed as '0.0'.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
			managing EMT (Early Morning TEAM)			
		EXE-CRT-VLD-03-001C-ACC-010	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing departure gaps during EMT	Very Large and Large Airports, Segregated mode operations	Whilst the ability to input departure gaps into ExCDS during EMT was considered acceptable, there was feedback given on the HMI design of the Spacing Status Window Functionality. One controller Strongly disagreed that the display of 'TFN' to show that a global spacing policy is in force was acceptable and would prefer more of an attention getter (e.g. either by having this text in a different colour or by having a designator automatically generated). A change required to current procedures was highlighted in terms of the distance specified by Tower when requesting departure gaps. Today the Tower will ask for the distance that they require when the lead aircraft reaches 4DME. With the Pairwise concept, the Tower needs to request the gap relative to the runway threshold. During EMT with departure gaps in force, the controllers observed indicator constraints changing from a spacing to a dependent for some aircraft pairs when leader passes 1 DME. This is correct system behaviour and shall be covered in training to ensure the controllers understand this system behaviour.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
		EXE-CRT-VLD-03-001C-ACC-011	The indicator support, HMI and associated procedures are found to be acceptable to controllers when managing tactical spacing gaps	Very Large and Large Airports, Segregated mode operations	Five out of six controllers agreed that they were able to input, edit and remove individual spacings effectively. One controller response was neutral, but commented that they need more exposure to using this functionality. For another controller, although they find the spacing functionality acceptable, they comment that this will 'take some getting used to' as it is a new way of using ExCDS than in current operations.	OK
		EXE-CRT-VLD-03-001C-ACC-012	The combined solution is found to be acceptable to controllers in missed or broken off approach scenarios	Very Large and Large Airports, Segregated mode operations	A blocked runway scenario was assessed on the second scenario day of the simulation. Several aircraft were instructed to conduct missed approaches, with several being broken off the approach and then the remaining aircraft switched to the other runway. The scenario worked successfully, with the controllers being able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs and missed approaches.	OK
		EXE-CRT-VLD-03-001C-ACC-013	The combined solution is found to be acceptable to controllers in aircraft speed non-conformance scenarios	Very Large and Large Airports, Segregated mode operations	During the operational scenario testing days of the simulation, several speed non-conformance scenarios were attempted. However, this was difficult to set up in a simulated environment. Despite this, the indicator procedures to adopt in	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
				mode operations	an infringement scenario were deemed to be acceptable by all participants.	
		EXE-CRT-VLD-03-001C-ACC-014	The combined solution is found to be acceptable to controllers in missing aircraft wake category information scenarios	Very Large and Large Airports, Segregated mode operations	An aircraft without a wake vortex category was assessed during the simulation. The tool behaved as designed and did not generate an indicator for this aircraft. The controllers were able to apply the defined procedures which require extra spacing to be applied ahead of and behind the aircraft and found this to be acceptable.	OK
		EXE-CRT-VLD-03-001C-ACC-015	The generation and display of the Early Line Zero to support the Base Leg turn is found to be acceptable to controllers	Very Large and Large Airports, Segregated mode operations	Qualitative feedback from controllers around ELZ were generally very positive, with participants agreeing that Early Line Zero is acceptable. The ELZ is seen as a benefit to the operation and useful as information to support the controller in the base legs turns, therefore improving predictability.	OK
EXE-OBJ-VLD-03-001C-EFF	To assess the impact of reduced MRS and PWS TBS on operational efficiency	EXE-CRT-VLD-03-001C-EFF-001	The average arrival movement rate increases when compared to the reference scenario	Very Large and Large Airports, Segregated mode operations	A benefit to arrival throughput is seen under all wind conditions, although the difference under light and moderate wind is not large enough to be highly indicative.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
		EXE-CRT-VLD-03-001C-EFF-002	The number of aircraft pairs that have minimum radar separation as their maximum constraint decreases when compared to the reference scenario	Very Large and Large Airports, Segregated mode operations	As the MRS constraint at threshold is reduced to 2NM as part of the Heathrow Pairwise concept, ROT becomes the maximum constraint for non-wake pairs in all but the high wind conditions, where wake separation minima are reduced to a greater extent. This prompts a sizeable reduction in the proportion of MRS pairs, when compared to the equivalent eTBS run.	OK
		EXE-CRT-VLD-03-001C-EFF-003	The effectiveness of the delivery of aircraft to the separation minima at the base leg stage is shown to acceptable	Very Large and Large Airports, Segregated mode operations	As a means of assessing the acceptability of separation delivery to the minima, the recorded events of technical losses of MRS were investigated. Based on post-analysis, it has been determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution, as no technical losses of MRS were reported in the solution scenario.	OK
		EXE-CRT-VLD-03-001C-EFF-004	The effectiveness of the delivery of aircraft to the separation minima at the intercept stage is shown to be acceptable	Very Large and Large Airports, Segregated mode operations	See above relating to EXE-CRT-VLD-03-001C-EFF-003.	OK
		EXE-CRT-VLD-03-001C-EFF-005	The effectiveness of the delivery of aircraft to the separation minima at the	Very Large and Large Airports, Segregated	See above relating to EXE-CRT-VLD-03-001C-EFF-003.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
			final approach stage is shown to be acceptable	mode operations		
		EXE-CRT-VLD-03-001C-EFF-006	The delivery conformance to the displayed indicators on the final approach is shown to be acceptable	Very Large and Large Airports, Segregated mode operations	For the displayed indicators (which only support wake and certain ROT pairs under eTBS), the aircraft position conformance to these indicators on final approach processed as a distribution, both at the 4DME and at 1DME points. These distributions demonstrate that the delivery conformance to the displayed indicators was acceptable, but is influenced by individual controller differences.	OK
EXE-OBJ-VLD-03-001C-ENV	To assess the impact of reduced MRS and PWS TBS on environmental efficiency	EXE-CRT-VLD-03-001C-ENV-001	Average CO ₂ emissions per flight are reduced when compared to the reference scenario	Very Large and Large Airports, Segregated mode operations	Fuel burn analysis indicates an average saving of 14.84kg per flight. Using the direct link between fuel burn and the amount of CO ₂ produced (3.15 times the mass of fuel burnt), this equates to an average CO ₂ saving of 46.73kg per flight.	N/A
EXE-OBJ-VLD-03-001C-HP	To assess the impact of reduced MRS and PWS TBS	EXE-CRT-VLD-03-001C-HP-001	Controller workload is shown to remain within acceptable levels	Very Large and Large Airports, Segregated mode operations	Generally speaking, controllers didn't feel like WL would change very much (although it was pointed out during debriefs that it is likely the FIN would take on more work than the INT and support from the GS and INT would be preferable), but rather their focal point and SA.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
	on human performance				They considered that the tools make monitoring easier: “providing more support for the controller must be a good thing” and decrease task load. However, due to RTS limitations, ATCOs couldn’t make a proper comparison between the PWS solution and the eTBS operations from baseline. Still, they stated that if the system was working well, it would have added in some workload, but they feel it would be normal and manageable.	
		EXE-CRT-VLD-03-001C-HP-002	Situational Awareness is shown to remain at the same level or is improved	Very Large and Large Airports, Segregated mode operations	During debriefs, controllers stated that having the ELZ indicator makes their controlling tasks easier in terms of judging the situation, making it more clear more quickly than just “eyeballing” it (as is the case in today’s operations). As such, the indicator supports controllers in drawing their mental picture and maintaining their SA. Moreover, according to the EOP survey, most ATCOs agreed that they could easily spot incorrect strip order and manage their strips to get reliable ELZ information during standard traffic and also breakoff/missed approach scenarios.	OK
		EXE-CRT-VLD-03-001C-HP-003	The likelihood and consequence of human error are assessed as	Very Large and Large Airports,	Not assessed	NOK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
			remaining within acceptable levels	Segregated mode operations		
		EXE-CRT-VLD-03-001C-HP-004	The procedures are found to be acceptable by controllers	Very Large and Large Airports, Segregated mode operations	Procedures were generally very well accepted by controllers. The results of the End-of-Participation questionnaire show that most APP controllers strongly agreed that indicators procedures are acceptable. All APP controllers agreed that the Pairwise procedures for transitioning to 2NM MRS on final approach enables them to achieve the required spacing or separation. TWR controllers strongly agreed that procedures for normal operations are satisfactory.	OK
		EXE-CRT-VLD-03-001C-HP-005	The Method of Operations are found to be acceptable by controllers	Very Large and Large Airports, Segregated mode operations	Multiple abnormal scenarios were run during the two scenarios days (e.g., breakoff, medical emergency etc.), for most of which operating methods were deemed acceptable by ATCOs. Degraded conditions were not simulated in the RTS because the analysis of failure modes is incomplete.	OK
		EXE-CRT-VLD-03-001C-HP-006	The teamwork and communication enabled	Very Large and Large Airports,	Not assessed	NOK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
			are shown to be acceptable	Segregated mode operations		
		EXE-CRT-VLD-03-001C-HP-007	User roles and responsibilities are shown to remain acceptable	Very Large and Large Airports, Segregated mode operations	Though it was not intended to include the Group Supervisor (GS) position in this RTS, it was possible to replicate the GS's expected input. Further clarification of the GS's responsibilities (e.g., interacting with the system or making phone calls to the controllers) is still needed, which should be investigated in the future phases of development. During RTS debriefs, APP controllers highlighted the importance for GSs to be considered in training, for them to understand how to better support the FIN, who according to them is expected to get more work.	POK
		EXE-CRT-VLD-03-001C-HP-008	User Confidence is shown to remain within acceptable limits	Very Large and Large Airports, Segregated mode operations	During RTS debriefs, controllers stated that they feel the introduction of the IA tools as a replacement of the current eTBS setup is a very big shift (with the biggest change in HMI). According to them, the shift is bigger than the one they experienced when switching from TBS to eTBS, feeling more like the initial switch from DBS to TBS, and it will require in-depth training to ensure the safety of operations.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
		EXE-CRT-VLD-03-001C-HP-009	The tool is shown to support the controllers in their decision making processes	Very Large and Large Airports, Segregated mode operations	The vast majority of APP participants strongly agreed in the EOP questionnaire that the tools adequately support their decision making and their performance of controlling tasks safely and efficiently. Additionally, TWR controllers felt confident that the system would support them enough in proactively resolving any infringement of the required separation/spacing between aircraft.	OK
		EXE-CRT-VLD-03-001C-HP-010	The tool is shown to provide sufficient, clear, accurate and timely information to the controller	Very Large and Large Airports, Segregated mode operations	The majority of controllers reported feeling like the ELZ information supported their task performance and was presented at the right time to support decision making. In terms of accuracy, some APP controllers' feedback during debriefs explained that the LZ felt slightly inaccurate. It is possible that this behaviour could be due to the SIM design, i.e., the average speeds of aircraft on final approach not being representative of operational data and should be investigated.	POK
		EXE-CRT-VLD-03-001C-HP-011	Controller trust in the integrity of the tool support and reliance on	Very Large and Large Airports, Segregated	APP controllers agreed that the IA tools are good, useful tools overall, which most of them (67%, n=6) found easy to use, according to EOP responses.	POK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion Title	Sub-operating environment	Exercise Results	Demonstration Objective Status
			indicators are shown to be acceptable	mode operations	ATCOs who are a bit more cautious or inexperienced would be supported by the indicator ("It brings the lower ones up" – for those ATCOs with less experience, the indicator may help them to become more efficient by having something to aim for). However, they still may be less inclined to be on the indicator or very close to it due to concern of infringing the indicator and having to take recovery action as a result.	
EXE-OBJ-VLD-03-001C-SAF	To assess the impact of reduced MRS and PWS TBS on operational safety	EXE-CRT-VLD-03-001C-SAF-001	The number of missed approaches due to insufficient spacing is no greater than in currently operations	Very Large and Large Airports, Segregated mode operations	The participating ATCOs did not indicate that missed approaches would be affected.	OK
		EXE-CRT-VLD-03-001C-SAF-002	Interoperability evidence can be produced to confirm that the elements of all solutions when combined do not degrade the level of safety.	Very Large and Large Airports, Segregated mode operations	The overall view from the ATCOs was that the interoperability of the solutions did not degrade safety.	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion Title	Sub-operating environment	Exercise Results	Demonstration Objective Status
		EXE-CRT-VLD-03-001C-SAF-003	The combined solution and procedures cause no losses of separation in the demonstration exercise	Very Large and Large Airports, Segregated mode operations	The ATCOs did not report any LoS associated with PWS using the new MRS rules. There were 11 technical losses of MRS during the eTBS runs. Through expert judgement, it was identified that in all but one case of the eTBS losses; the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way. Based on this analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution. See A3.2.2 for more details.	OK
		EXE-CRT-VLD-03-001C-SAF-004	The combined solution and procedures cause no increase in the frequency of go arounds when compared to the reference scenario	Very Large and Large Airports, Segregated mode operations	See EXE-CRT-VLD-03-001C-SAF-01 above	OK
EXE-OBJ-VLD-03-001C-SEC	To assess the impact of reduced MRS and PWS TBS	EXE-CRT-VLD-03-001C-SEC-001	A Security Risk Assessment is carried out	Very Large and Large Airports, Segregated mode operations	In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with	OK

Demonstration Objective ID	Demonstration Objective Title	Success Criterion ID	Success Criterion	Sub-operating environment	Exercise Results	Demonstration Objective Status
	on operational security				the SESAR methodology. As part of this, Security Risk Treatments were also applied.	
		EXE-CRT-VLD-03-001C-SEC-002	Security Risk Treatments are applied	Very Large and Large Airports, Segregated mode operations	In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with the SESAR methodology. As part of this, Security Risk Treatments were also applied.	OK

Table 18: EXE-VLD-03-001C Results

A.3.1.1 Results per KPA

This section provides a comparison between the performance results obtained in EXE-VLD-03-001C and those that were reported in the equivalent V3 exercises for RECAT-EU-PWS under Wave 1 Solution PJ.02-01:

Capacity

PJ.02-01 findings

The evidence obtained in the RTS02 indicated gains in runway throughput with the TB PWS concept with ORD tool compared to current operations of ICAO DBS and no controller tool support. The exact gains depended on the controller and their working method both without and with the ORD tool.

RTS4b showed there to be an increase in arrival throughput between Reference (RECAT-EU and no tool) and PWS with ORD tool scenarios (up to +4.1 [ac/h]). When pairs of aircraft delivered with under-spacings more than 0.25NM are excluded from the analysis, this increase in throughput values is slightly more pronounced (up to +4.6 [ac/h]). However, it should be noted that the benefits in throughput capacity varied depending on the ATCO configuration and depended on the working methods of the ATCO configuration in both the reference and PWS-A and ORD solution scenario.

FTS09 showed that compared to RECAT-EU TBS with FTD only, throughput is higher when RECAT-EU-PWS is used in segregated runway operations in the different wind conditions tested. For Strong Headwinds, the results increase from a minimum of 5.3% to a maximum of 5.9% when the traffic pressure is coordinated. Without traffic pressure coordination, throughput increases from a minimum of 0.6% up to 3.5%, depending on the wind conditions experienced.

VLD3 findings

Under this exercise, the arrival throughput was assessed under a range of wind samples. However, the data set and the consistency of seating configurations for the matched run pairs was constrained. Depending on the wind profile and runway direction, a segregated runway capacity impact of **-0.2** to 3.4 movements/hour (**-0.44**-8.11%) was identified. Note: values in red indicate a performance reduction.

These findings are in a similar range to those reported in Wave 1, although these were conducted using the EUROCONTROL tool solution and did not include the same indicator support, MRS rules or number of aircraft types included in the RECAT-EU-PWS separation scheme.

Fuel Efficiency

PJ.02-01 findings

Compared to RECAT-EU TBS with FTD only, the average fuel burn per flight is reduced, with savings depending on the wind conditions. When traffic is coordinated, up to 3.7% fuel saving can be obtained. Without traffic pressure coordination savings can be up to 2.3%, depending on the wind conditions.

VLD3 findings

In this exercise, an average of 14 seconds of holding per flight was saved, which corresponds to 14.84Kg of fuel saving per flight, or 46.73kg of CO₂ saving per flight.

Safety

PJ.02-01 findings

No under-spacings were observed in RTS02 with segregated runway operations for either the solution scenario TB PWS with the ORD or the reference scenario. There was no increase in separation non-conformances before alignment or on the base leg due to the use of TB PWS with ORD tool. In RTS4b, the number of under-separations (small and large) was, at least, not higher in the solution compared to the reference runs.

VLD3 findings

Based on post-analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution, as no technical losses of MRS were reported (11 were reported during eTBS runs).

A.3.1.2 Results impacting regulation and standardisation initiatives

None of the findings provided above indicate any need for additional updates to standards or regulations, beyond what is already being introduced to support the deployment of the Heathrow Pairwise concept. NATS will be engaging with the UK CAA to obtain the required regulatory assurance to deploy all related updates to separation standards into Heathrow operations.

A.3.1.3 Coverage of Wave 1 Contextual Note Future R&D Recommendations

A number of recommendations were included in the Contextual Notes for the related Wave 1 solutions to be addressed in future R&D. The extent to which these recommendations have been addressed under VLD3 is summarised below. Please note that the recommendations were defined in the context of the EUROCONTROL solution, rather than the NATS tools:

Wave 1 Recommendation	Action taken under VLD3 (WP2)
Existing or new aircraft types could be assessed to further extend the 96x96 wake separation scheme	The RECAT-EU-PWS wake separation scheme has been expanded to a 103x103 matrix and validated under the Wave 2 activities of Solution PJ.02-01-04 'Wake turbulence separations (for arrivals) based on static aircraft characteristics'. EXE VLD-03-001C validated pairwise separations using a smaller matrix, which has been defined based on the aircraft types that are common at Heathrow Airport
In certain wind conditions, using 2.5NM MRS could increase the risk of consecutive go-arounds as the ROT may increase and, which could negate the benefits in arrival throughput capacity. One of the suggested solutions could be to identify the optimal wind conditions and corresponding parameters that allowed 2.5NM MRS based on ROT to be applied. An alternative solution could be also the adaptation of the LORD tool parameters, e.g. in certain wind conditions, an extra buffer could be added to the ROT in strong headwind	EXE VLD-03-001C included the validation of updated procedures related to the point on the approach that MRS is reduced from 3NM, to 2.5NM, to 2NM. Although this activity did not directly address this Wave 1 recommendation (due to the simulation not being able to measure true go-arounds as there was no Tower

Wave 1 Recommendation	Action taken under VLD3 (WP2)
conditions. Further studies are recommended to investigate the optimal wind conditions allowing the application of minimal separation values without the risk of go around	'out-of-the-window' position), the concept is designed to manage consistent clearance to land margin at threshold and the tool considers aircraft types and wind conditions. The wider analysis and safety assurance strategy will provide the necessary assurance.
An adequate buffer should be integrated into the ITD/LORD tool to accommodate for variability related to aircraft performance on the descent profiles. The size of the buffer should be based on the analysis of the aircraft performance data derived from operational data collected from the airport in which the concept is to be implemented. The local safety case should be conducted before the implementation (applicable to ITD/LORD tool only).	The tool will be calibrated and validated using real world speed performance on final approach and ROT data over a large time period. This activity will demonstrate the safety requirements at runway threshold (to manage under separation and clearance to land margin) are met.
It is recommended that the FTD HMI could be colour-coded to display the different constraints: the ROT, WT or MRS to support the ATCO situational awareness (applicable to FTD and ITD/LORD tools).	In the Heathrow Pairwise concept, constraint types are distinguished to separate wake and dependent constraints from all other constraints for the controllers' situational awareness
It is recommended that the FTD HMI could be highlighting when FTD is infringed to indicate immediate need for go around (applicable to FTD and ITD/LORD tools).	The Heathrow pairwise concept includes functionality for a 'wake breakthrough' indicator if the aircraft is near a wake constraint (where the largest constraint is not wake). In addition, ATC procedures dictate specific scenarios where an aircraft shall be broken off the approach.
It has been recognised that with the ITD/LORD tool the controllers were less aware of the aircraft type and their wake vortex categories. This could rise to a safety issue in the scenario of reverting to 3NM MRS and DBS separations with no ITD/LORD tool such as in a degraded mode (i.e. loss of tool support). Adequate refresher training should be provided to ensure the controllers are able to maintain those skills. Furthermore, contingency procedures developed for degraded modes of operations should take the potential loss of current skills into considerations in their design.	A training syllabus for Pairwise implementation has been designed and will be amended based on the findings of EXE VLD-03-001C.
To be able to work with the tool confidently and comfortably controllers need to have sufficient training and time to familiarise themselves with the tool and the changes in working methods that result from working with both the FTD and ITD/LORD tool, prior to implementation.	As above
To increase the confidence in the results obtained with the TB PWS for arrival concept with ITD/LORD with ROCAT it is recommended to conduct alternative studies. Further studies could consider different traffic samples / increase the variety of aircraft pairs or different runway configurations.	A wide range of operational and meteorological conditions were included in the experimental design for EXE VLD-03-001C to provide adequate coverage of possible operations and provide variety. EXE

Wave 1 Recommendation	Action taken under VLD3 (WP2)
Additionally, use of different validation techniques such as fast time simulation is also recommended to increase the reliability of the results.	VLD-03-001C was originally intended to be a shadow-mode trial exercise, however this could not be supported within the available SESAR timeline.
Finally, the legal aspect of responsibility in case of a loss of separation due to the FTD and /or ITD/LORD tool miscalculation needs to be addressed prior to implementation. The legal framework describing clearly the roles and responsibilities between controllers, air traffic service providers and tool developers need to be produced before the implementation into an operational environment.	As per the safety case developed to support the deployment of the Heathrow Pairwise concept, the tool support is assured to the necessary level to allow controllers to work to the displayed indicators and not be legally responsible for any separation losses as a result of miscalculation.

Table 19: VLD3 coverage of Wave 1 CN recommendations

A.3.2 Analysis of Exercises Results per Demonstration objective

A.3.2.1 EXE-OBJ-VLD-03-001C-ACC Results

As the Heathrow Pairwise concept has been validated previously at lower maturity levels, a focus for this simulation was to secure in-depth subjective data on potential refinements to the interface, the behaviour of the presented indicators and the associated procedures. As well as questionnaires completed at the end of each run and at the end of each participant's involvement in the exercise, observations and debrief comments were also extensively recorded and compiled to capture discussions and events. The combined findings relating to controller acceptability are provided in the section below.

Impact of Runway Configuration and Wind Conditions

Survey responses report that all controllers found the Pairwise concept and functionality acceptable in all runway operating configurations. Similarly, all controllers also agreed that the Pairwise concept was acceptable across all wind conditions. Qualitative responses from controllers did not note any differences in the tool behaviour depending on wind or runway in use and that the system would work effectively in any of these conditions in current operations.

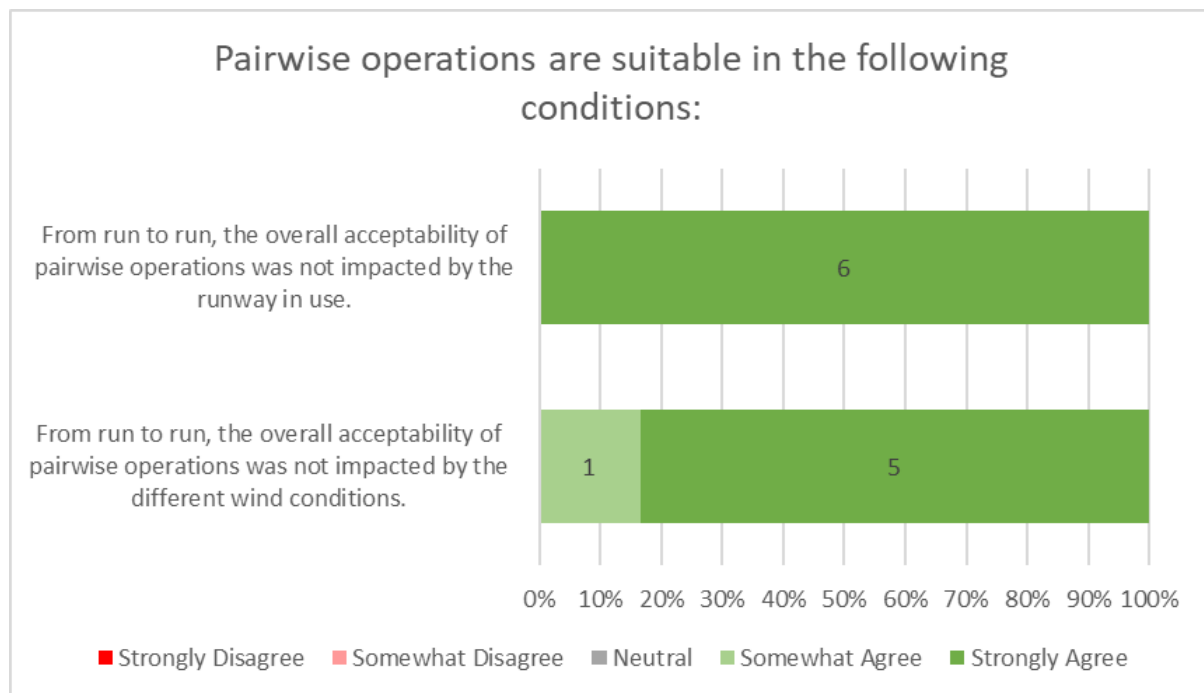


Figure 13: Acceptability of Pairwise under all runway configurations and differing winds

Acceptability of HMI and Indicator Support

The eTBS system currently displays indicators for wake separation pairs, and for ROT pairs behind Upper, Heavy and Super aircraft where ROT is the largest constraint relative to the wake separation. Indicator types for all separation/spacing constraints are supported by the Heathrow Pairwise tool.

Across a range of operational contexts, controllers found HMI and indicator support acceptable. Controllers generally found the system and HMI intuitive and understood system behaviours. See Figure 14 below:

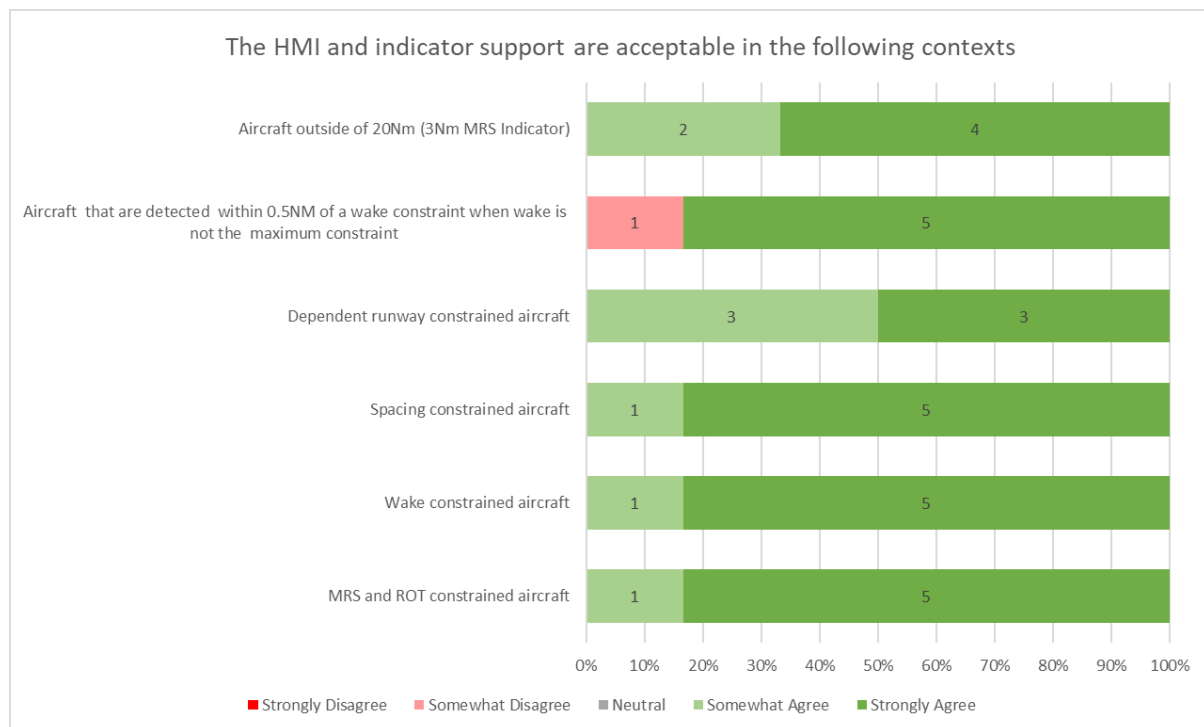


Figure 14: Acceptability of HMI and indicator support for all separation and spacing constraints

Regardless of the maximum constraint, the indicator support and HMI were found to be acceptable to controllers.

Support for Aircraft when outside 20NM using the 3NM MRS indicator was considered acceptable by controllers, with two controllers somewhat agreeing to the overall acceptability in this scenario with the remaining four strongly agreeing. One controller commented that they can only give feedback on the 3NM MRS indicator based on earlier development simulations as they did not see it in this simulation. There were some runs where the wind conditions were such (i.e., tailwind) that even outside of 20DME the indicators were calculated greater than 3NM. Feedback from some controllers indicated that they did not feel the 3NM MRS indicator should be shown within 20DME even if follower aircraft was outside of 20DME as it was irrelevant. Similarly, indicator behaviour and HMI for dependent runway-constrained aircraft was acceptable to the controllers, but only three strongly agreed, whilst the other three rated this somewhat agree. One controller did not like the ELZ for dependent aircraft being displayed as '0.0' commenting that "0.0 works fine but it isn't particularly relevant to anything".

Some controllers observed indicators changing from a spacing to a dependent constraint for some aircraft pairs when the leader passes 1 DME. This is correct system behaviour and correctly reflects the constraints as they update. These scenarios shall be covered in training to ensure the controllers understand this system behaviour.

During the simulation the controllers commented that they observed indicators pulling away when the lead aircraft passed 4DME. It was suspected that this behaviour may be caused by the aircraft speed performance in the simulator. Therefore, it is recommended that a review of the simulator performance inside 4DME is conducted to ensure that it is consistent with operational data.

Acceptability of the Wake Breakthrough indicator (when an aircraft is detected within 0.5NM of a wake constraint when wake is not the maximum constraint) was generally accepted, as five of six controllers strongly agreed that HMI and indicator support was acceptable; however, one controller somewhat disagreed, arguing that 0.5NM is insufficient for a breakthrough, and that 0.75NM could be more suitable, to give an additional buffer for recovery. However, it should be noted that the Wake Breakthrough behaviour is the same in Pairwise as it is in eTBS today.

Acceptability of Procedures

In addition to the acceptability findings presented above in relation to the HMI and indicator presentation, participants also provided ratings on the associated procedures; as provided in Figure 15:

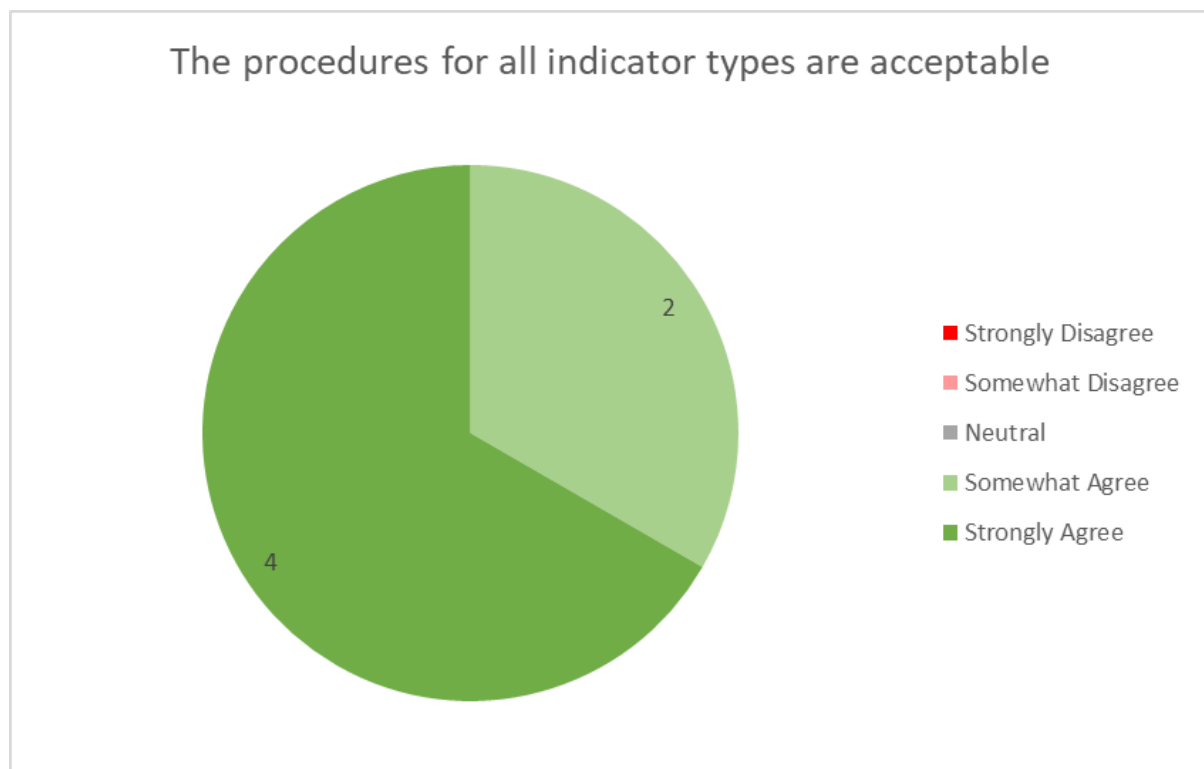


Figure 15: Acceptability of ATC Procedures for all Indicator types

All participants were in agreement that the defined procedures are acceptable, as defined in the ConOps. Supporting comments suggest that the alignment of new procedures with those pre-established in eTBS operations increases their acceptability. Others had a more neutral response, stating that while they are “not ideal in each individual scenario, they provide consistent procedures across the board”.

One participant provided a detailed comment on the benefits and drawbacks of implementing simple and consistent procedures. Where this reduces the potential for human error and training complexity, it may also lead to potential operational inefficiencies due to controllers being required to initiate a go-around under certain conditions. Nevertheless, the participant responses to the defined procedures remains positive.

From the perspective of tower controllers, both of the two tower controllers involved strongly agreed that procedures for all indicator types, including when aircraft ahead of the indicator are acceptable. They also agreed that they were able to anticipate a possible deterioration in spacing/separation between aircraft.

A component of the Heathrow Pairwise concept is the reduction of MRS from 2.5NM to 2NM on final approach, as well as rule changes to allow an earlier reduction from 3NM to 2.5NM in the RMA. To support this, operational procedures have been amended to protect against losses of separation. As such, validation participants were asked to indicate whether the combined procedures and indicator support provided are acceptable in supporting achieving required separation/spacings. The provided responses are presented below in Figure 16:

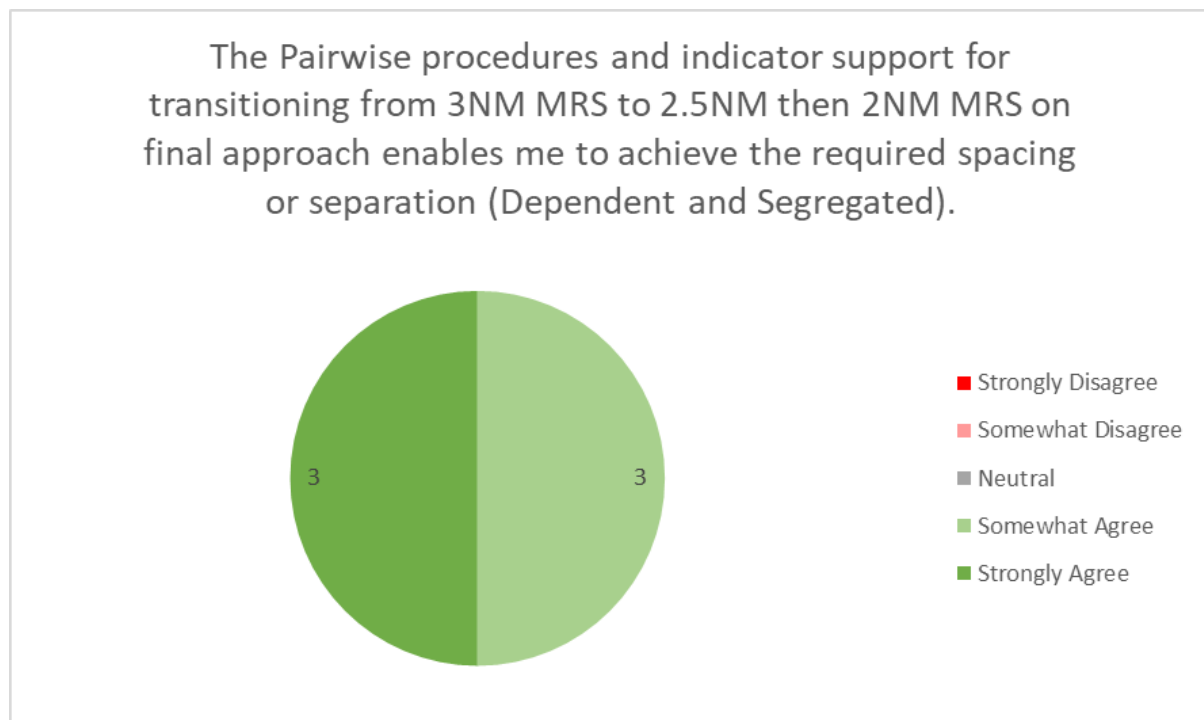


Figure 16: Acceptability of ATC Procedures for the transition of 3NM to 2NM on Final Approach

All responses were positive, with participants agreeing this support is acceptable for operations. Additional comments provided reinforcement that the support is “fail safe” and is “a logical procedure”. One controller commented that the ability to transition from 3NM to 2.5NM sooner than today is a ‘must’, particularly when certain wind conditions allow spacings below 3NM, as this spacing is difficult to achieve with the current rules.

One participant raised some concern that it may become easier to lose 2.5NM separation in the phase between turning onto the base leg and establishing on the final approach due to the line zero value and indicator for the 2.5NM constraint ‘tempting’ the controller to attempt to achieve this without having vertical separation. This scenario should be highlighted during training and there was a suggestion of introducing a standardised drop to a higher altitude than used in the current operation to give the final approach controller the option to use vertical separation. Being able to use vertical separation in such conditions is a considerable advantage, however, this may result in fewer continuous descent approaches, and some airlines may request to descend sooner.

Acceptability in Spacing Scenarios

As part of the End Of Participation (EOP) questionnaire, all participants provided ratings against the acceptability of the concept functionality against a full set of spacing scenarios which were simulated on two days of the exercise which focussed specifically on generating a range of operational scenarios. As one of the six participants did not take part during those days, their ratings have been removed from Figure 17 below:

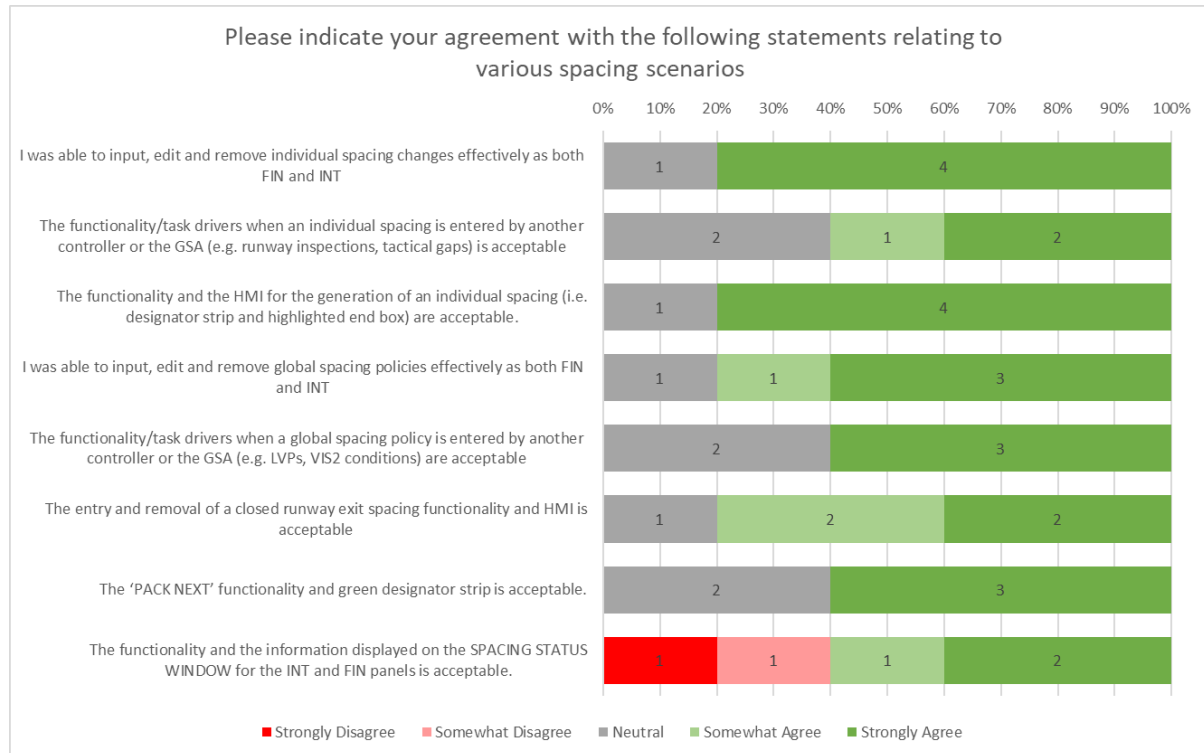


Figure 17: Acceptability of Spacing Scenarios

Overall, eight specific functions were highlighted in the questionnaire which have been developed based on a human-centred design process to support the straightforward application of spacing changes within the Heathrow operational context.

Whilst none of the statements presented to the controllers received unanimous positive responses, the participants left several encouraging comments. For example, “although I hadn’t seen [the Heathrow Pairwise concept] for a while, I found it straight forward to pick up all of the above functionality”. Most neutral responses were from one participant, who commented that they “need more exposure to these events to be sure”.

Five out of six controllers agreed that they were able to input, edit and remove individual spacings effectively. One controller response was neutral, but commented that they need more exposure to using this functionality. For another controller, although they find the spacing functionality acceptable, they comment that this will ‘take some getting used to’ as it is a new way of using ExCDS than in current operations.

During Runway inspections, it was noted that in the majority of cases, the lead aircraft will land before the follower has turned base leg and therefore the ELZ value will be lost (and therefore no indicator generated), or if the aircraft has turned base then the indicator and LZ will be lost. This was discussed during the debrief and all of the controllers felt this was not an issue, as they are able to remember the 4DME indicator value and 'round up', and if not, refer to the threshold value that is displayed on the designator. There was no concern regarding safety, due to the fact it is a spacing gap rather than a separation. This will also be covered during training.

Not all participants were exposed to the "PACK NEXT" functionality (in support of operations on the departure runway), or did not recall what function the term referred to when filling in the questionnaire, hence the two neutral responses. However, no objections were raised regarding this functionality during the simulation when it was tested.

Only the new Spacing Status Window received negative responses. The Spacing Status window, shown at the top of the FIN/INT ExCDS bay and displays current Spacing policy information. This was justified by comments stating that "the spacing status window does not display information in such a way that grabs my attention" and "I don't find the box draws my attention to it. I don't feel the way the data moves across is very intuitive".

During the operational scenarios a transition from VIS1 to VIS2 to LVPs and reverting back again was simulated. During the debrief the controllers commented that they found the indicator support to be acceptable. However, the comments made previously with regard to the information in the Status Spacing Window are also relevant here.

Another function that requires further refinement is the entry and removal of a closed runway exit spacing policy via the ExCDS interface. It was suggested that the interface design will be further refined following this validation exercise.

A discussion occurred between one of the observing Tower controllers and Approach during a scenario where the Tower calls and requests departure gaps during EMT. In current operations, the Tower will ask for the distance that they require when the lead aircraft reaches 4DME (for example, 6NM), which allows for compression between the leader and follower past 4DME. With the Pairwise concept, the Tower needs to request the gap relative to the runway threshold. This will be the value that is entered into the Spacing tool, and then the tool calculates the indicator distance to ensure that the threshold distance is met. Therefore, this is highlighted as a new way of operating between Tower and Approach and should be emphasised in training.

Acceptability in Other Scenarios

A blocked runway scenario was engineered on the second scenario day during the simulation. The Tower called Approach to inform that the runway was blocked due to an aircraft experiencing a burst tyre on landing. This resulted in several aircraft being instructed to conduct missed approaches and several being broken off the approach and then the remaining aircraft switched to the other runway.

The scenario worked successfully, with the controllers being able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs. Both of the two tower controllers involved strongly agreed that procedures for a blocked runway with multiple missed are acceptable.

During the operational scenario testing days of the simulation, attempts were made to engineer several speed non-conformance scenarios. This proved to be difficult to set up in a simulated environment, however the indicator procedures to adopt in a scenario of infringing an indicator were deemed to be acceptable by all participants.

A scenario of an aircraft without a wake vortex category was engineered during the simulation. As expected, the tool behaved as designed and did not generate an indicator for this aircraft. The controllers were able to apply the defined procedures which require extra spacing to be applied ahead of and behind the aircraft and found this to be acceptable.

Acceptability of the Early Line Zero Function

The Pairwise system provides an early indication of the required separation or spacing which is displayed in Early Line Zero (ELZ) on the aircraft track data block on the radar display. Controllers were presented with a range of statements relating to ELZ (see Figure 18). Responses from controllers in this case were generally very positive, with participants agreeing that Early Line Zero is acceptable and supports their tasks.

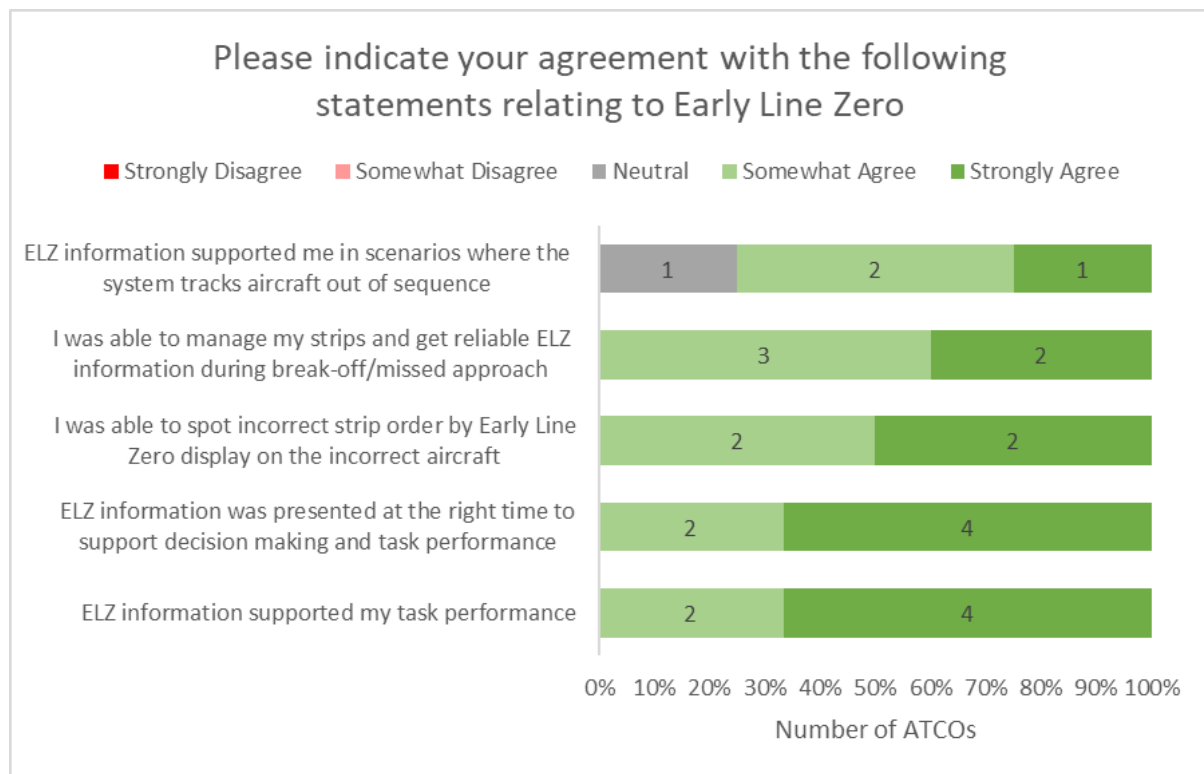


Figure 18: Acceptability of Early Line Zero Support

One controller commented that *'I am not user of LZ, so ELZ is of limited benefit right now. I can see how it is helpful to others'*. The controller in question was asked to clarify this response, as ELZ is not present in eTBS today. The controller explained that, in current eTBS operations, they can make the base leg turn using their knowledge of RECAT-EU spacing and their own judgment.

During the simulation, the controller found that they were still using their current knowledge/judgement and not paying attention to the ELZ. They felt that additional exposure to the function is needed to inform their acceptability. However, with the introduction of Pairwise, the complexity of the separation and spacing calculations will increase and ELZ is therefore expected to support the most efficient delivery.

As described previously, a blocked runway scenario was engineered which resulted in several aircraft being instructed to conduct missed approaches and several being broken off the approach and then the remaining aircraft switched to the other runway. The controllers were able to understand the information being displayed to them when the aircraft sequence changed due to the break-offs and missed approaches.

Operational Acceptability Conclusion

Overall, all aspects of the Pairwise concept have been considered to be acceptable. There is a recommendation to make refinements to some of the ExCDS Spacing functionality such as the display of the Status Spacing Window and the HMI in support of closed runway exits.

A.3.2.2 EXE-OBJ-VLD-03-001C-EFF Results

The primary driver for the introduction of the Pairwise concept is the potential for greater arrival throughput efficiency. In light of this, a matched experimental design was applied to determine the capacity gains that could be yielded by the solution. Additionally, the delivery conformance to the separation minima and displayed indicators was investigated to highlight any gap between what the separation rules allowed for and what was achieved by the participating controllers. The following section highlights the key findings from this analysis:

Arrival Throughput Analysis

A set of representative wind samples were used in the matched pairs: a light wind sample for both runway directions, a moderate sample on 09L and a strong sample on 27L. A simplified description of these wind samples is provided in Table 20 below, to give context to the findings provided later in this section:

	Surface		1000ft		3000ft	
	Speed	Headwind	Speed	Headwind	Speed	Headwind
Light (27L/09R)	5	4-5	6-7	5-7	4-11	4-11
Moderate (09L)	10	7	16	15	24	24
Strong (27L)	14	14	21	21	33	33

Table 20: EXE-VLD-03-001C Wind Sample Summary

While a fully matched experimental design was planned, staffing limitations on the execution dates prevented this. It is expected that the objective data analysis was affected by this, particularly where findings were similar under reference and solution conditions. Due to preliminary findings, the experimental design was adapted part-way through the activity to introduce the moderate and heavy samples to the matched runs – which did not allow for them to be simulated in both directions. The findings are therefore sensitive to the influence of the small size of the data sample and disruption to the matched design. The quantitative results should therefore be interpreted with care and alongside the qualitative conclusions presented in this report.

To generate the required metric for airport capacity (CAP3.2), the count of aircraft landed during each measured run was logged. Due to the length of the traffic samples, the duration of the recorded part was 45 minutes, which was then extrapolated up to 60 minutes to provide the hourly rate of movement. For this reason, Figure 19 shows movement values that are not integers:

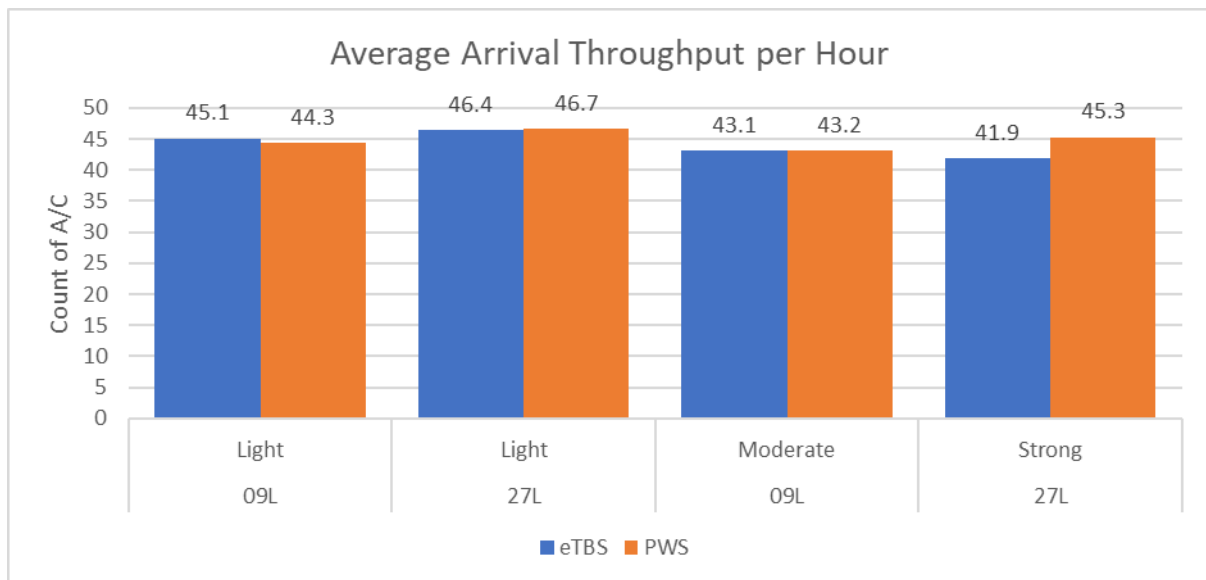


Figure 19: Comparison of arrival throughput under different wind levels

The Pairwise solution is expected to deliver benefits due to:

- The change from the RECAT-EU to RECAT-EU-PWS wake turbulence separation scheme which would be expected to reduce the mean wake turbulence separation in all wind conditions (subject to the MRS constraint);
- The introduction of a 2NM MRS on final approach supported by tailored ROT indicators which would be expected to reduce the mean MRS or ROT spacing delivered at 4DME below the 3NM baseline values as the strength of the headwind conditions increase.

The results presented in see Table 20 confirm the increase in landing rate in strong wind conditions. A considerably greater headwind component at all levels in this sample increases the proportion of non-wake pairs able to use less than 3NM spacing delivered to 4DME. Overall, a benefit to arrival throughput is seen under all conditions.

However, a low or marginal benefit is seen in Light and Moderate wind conditions for the 27L runway which is not fully in-line with the pre-validation expectations. The effects of the traffic mix and wind conditions are explored in the sections below. A marginal decrease is seen for the 09L runway direction in light wind conditions. This is understood to be due to the calibrated ROT spacing values being more conservative in this direction.

Via debrief notes, it was reported that *'ATCOs feel that [Heathrow Pairwise] might bring about a benefit of greater consistency in terms of runway capacity. Some controllers today can be more conservative when aiming for separations, so therefore there is a bell curve of throughput delivery. Having indicators for all aircraft pairs may have the impact of "flattening the curve"'*.

The exercise activity was conducted using an interim set of adaptation that controls the Pairwise system and, in particular, the calculation of the indicator distances. Further refinements to this adaptation are expected in the future. It is possible that a degree of conservatism was present in the ROT adaptation and there may therefore be scope for further optimisation subject to maintaining acceptable clearance to land behaviour for the system overall.

Analysis of Maximum Separation/Spacing Constraints

Due to the MRS minima reduction introduced as part of the concept, it is anticipated that the proportion of aircraft pairs with MRS as the maximum constraint at threshold will reduce. To confirm this, analysis was undertaken to highlight the shift in the proportion of aircraft with an MRS constraint with the change to Pairwise. Despite non-wake pairs not receiving indicators in the eTBS tool, it is possible to still determine maximum constraint for each aircraft pair from the platform logs.

The tool logs were analysed to show the max constraint for aircraft under each scenario. These results are presented by the combinations of wind and traffic sample, of which there are four. Higher counts are shown for the light wind samples, as these were run in both runway directions. In this context of Figure 20 below:

- 'HMEDS' refers to a very high proportion of Medium Category aircraft in the traffic mix;
- 'MIXHM' indicates a more even mix of Heavy and Medium Category aircraft.

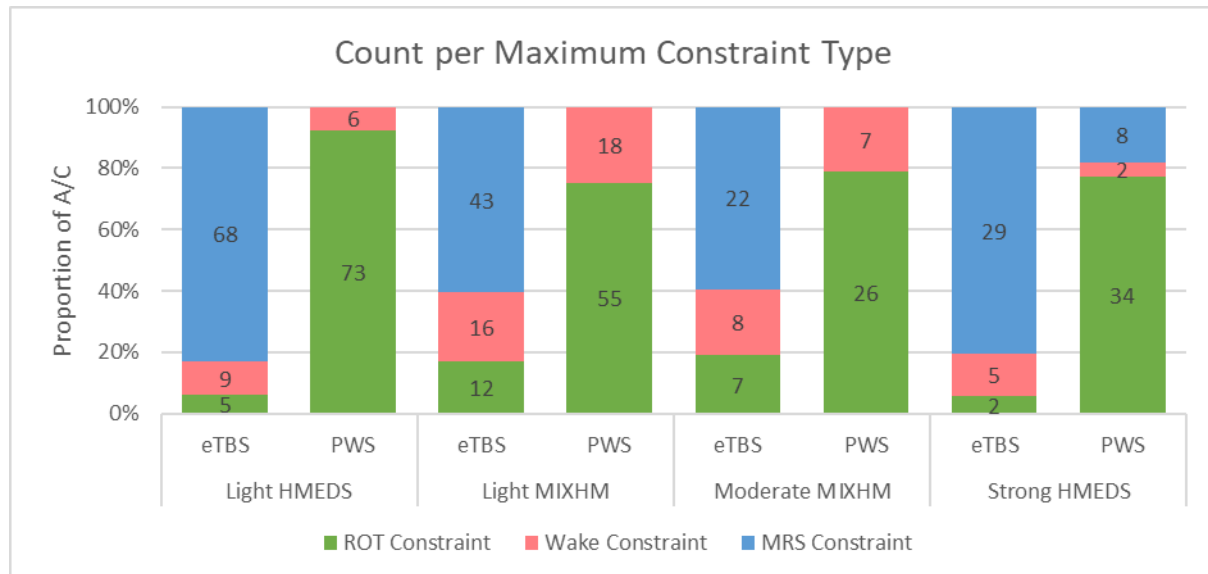


Figure 20: Maximum constraint type per wind-traffic combination

As can be expected for both tools, the proportion of wake pairs reduces in samples with a greater number of Medium aircraft; meaning that fewer lead aircraft generate a wake constraint. In these traffic mixes, the proportion of ROT spacing pairs increases in nearly all cases. For the ‘MIXHM’ samples, the wind conditions did not have a large impact on the proportion of wake pairs.

As the static MRS constraint under eTBS operations is 2.5NM at threshold, this is the maximum constraint for aircraft pairs that do not have a wake constraint (e.g. medium-medium pairs). This is demonstrated by the large proportion of MRS pairs in all conditions.

MRS constrained pairs were only present in strong wind conditions for Pairwise runs, as the wake and ROT values are reduced during periods where there is high headwind. As the MRS constraint at threshold is reduced to 2NM as part of the Heathrow Pairwise concept, ROT becomes the maximum constraint for non-wake pairs in all but the high wind conditions, where wake separation minima are reduced to a greater extent.

Delivery of Aircraft to Separation Minima

Instances were analysed in which a technical loss of MRS was recorded. These are referred to as “technical” losses as a simplistic analysis method was used, whereby radar tracks were used to identify potential losses of lateral separation (when aircraft had less than 1000ft vertical separation). These were then checked manually in the radar recordings to confirm if they were genuine losses.

The count of technical losses of separation are presented below in Table 21, which splits the events by the positions of the two aircraft involved. Note that some losses were difficult to verify as they lacked operational context (e.g. ATC can request confirmation from the pilot if they are established). The values below are therefore considered conservative and should be interpreted more as an measure of the pressure on the separation minima under the reference solution; in particular around the turn to base leg.

Category	eTBS Count	Pairwise Count
Leader on intercept, follower on base leg	9	0
Both aircraft on base leg to intercept	1	0
Both aircraft on final approach	1	0

Table 21: Summary of technical losses of MRS

There was a total of 11 technical losses of MRS during the eTBS runs while there were 0 technical losses in the PWS runs using the new MRS rules. Based on this brief analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution.

Through expert judgement, it was identified that in all but one case of the eTBS losses; the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way.

Delivery Conformance to Displayed Indicators

Once indicators are generated for the relevant aircraft following the base leg turn, it is possible to conduct further analysis on operational efficiency via delivery conformance. For the displayed indicators (which only support wake pairs under eTBS), the aircraft position conformance to these indicators on final approach processed as a distribution, both with the leader at the 4DME and at 1DME points.

For the purposes of the visualisations shown in Figure 21 and Figure 22 below, distance values were rounded to the nearest 0.1NM and any values greater than 2NM were discounted:

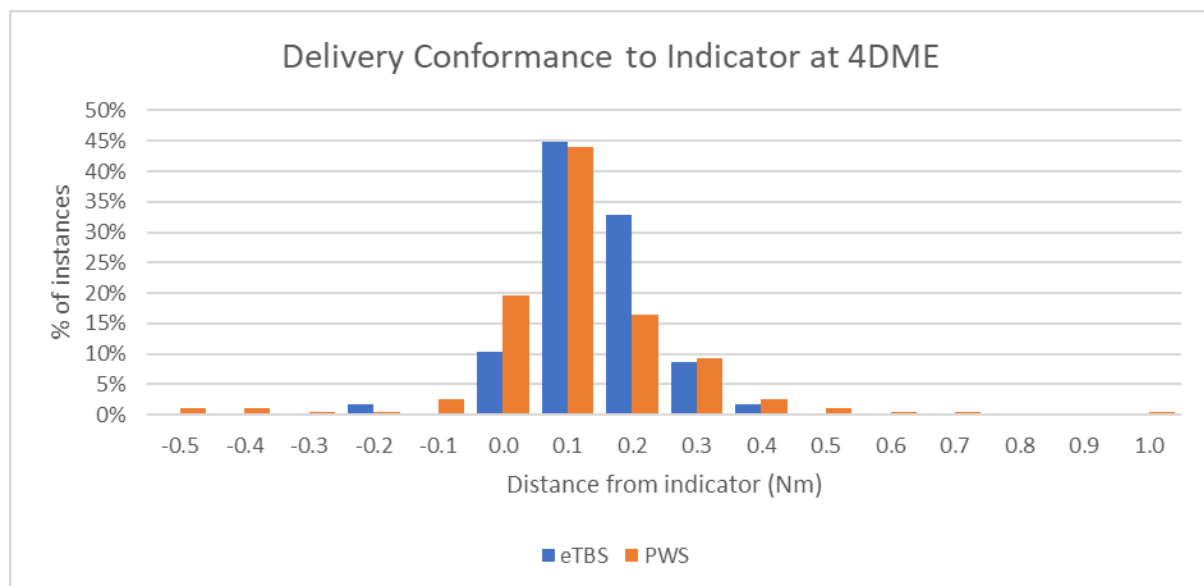


Figure 21: Delivery conformance to indicator at 4DME

As shown by the figure above, a greater proportion of aircraft are positioned on the indicator (0.0) under Pairwise operations compared to the eTBS reference, as well as an equal proportion positioned at +0.1NM. The impact of the inconsistent seating configuration between the runs in the same matched pair is likely to have had a confounding influence on this and should be considered.

In relation to the distribution where the leader aircraft is at 1DME (see below), some large gaps (0.5-1.0NM) were seen only during Pairwise runs. A potential cause of this was highlighted in the observation notes, which noted 'ATCOs commented that they observed indicators pulling away when the leader passed 4DME'. This was suspected to be a 'simulator issue'.

With respect to those aircraft that infringed the displayed indicators (-0.1 to -0.5NM), system limitations required the first aircraft in the sample to land before the eTBS tool or Pairwise tool was activated. By this point, under both scenarios, participants had already positioned a stream of aircraft on the final approach behind this first aircraft. There were instances where participants found that the aircraft infringed their indicators when they appeared, as represented in the figure above. As far fewer indicators are provided by the eTBS tool, far fewer instances of this were recorded under the reference scenario.

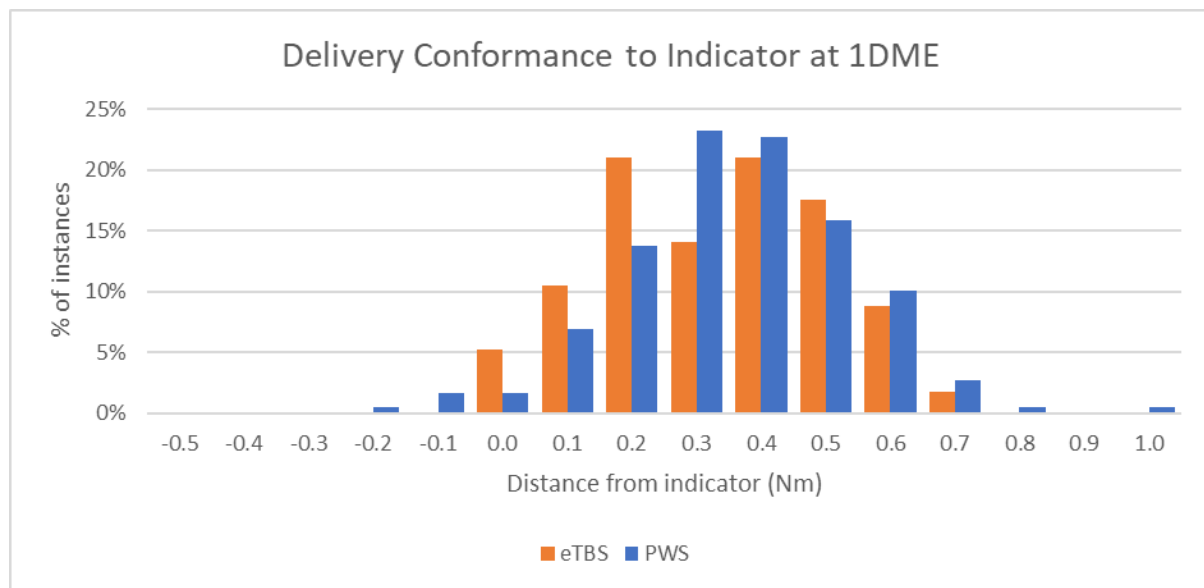


Figure 22: Delivery conformance to indicator at 1DME

The shift in distribution in the second figure demonstrates the 'pull away' effect described above, whereby the compression calculation caused the indicators to move further ahead of the aircraft once the leader was within 4DME. At 1DME, while the Pairwise functionality and procedures produced a more even distribution of conformance, a lesser proportion of aircraft were positioned on (or just behind) the indicators than the eTBS curve. A smaller number of infringements at this point were recorded under reference conditions (eTBS), although the cause of these could not be identified through log analysis.

For further understanding, a summary of the mean distance to displayed indicators at each point on the final approach is given in Table 22 below:

	4DME	1DME
eTBS	0.14	0.33
PWS	0.12	0.36

Table 22: Summary of average distance from the displayed indicator (NM)

These values show little difference between the two toolsets, which could well be influenced by the change in participants between the two scenarios in each matched pair. That said, no mean difference was predicted prior to the validation exercise.

Operational Efficiency Conclusion

Although based on a small data set, the analysis above indicates that efficiency benefits can be gained through the introduction of the Pairwise concept with no degradation on the conformance to the Wake and MRS minima. In fact, these results suggest an improvement in compliance in the base leg area due to the revised procedures. Further optimisation of the system adaptation, subject to the system safety and performance outcomes being maintained, may result in additional benefits.

A.3.2.3 EXE-OBJ-VLD-03-001C-ENV Results

Due to the traffic samples selected to support the exercise, the analysis is based on two one-hour windows, 10:00 – 11:00 and 21:00 – 22:00. It is therefore assumed that the average impact during these hours apply between 06:00-22:00 UTC which will exclude the first hour of TEAM operations from the analysis. The base year for the analysis is 2019, since this is the last full year which is not impacted by Covid-19.

The total number of holding minutes saved as a result of PWS is calculated in two parts, the reduction in average holding time and the reduction in the number of flights that hold.

The reduction in average holding time for an hour is calculated as the number of extra movements multiplied by the average holding time per holding flight in the hour. This was calculated for all hours (06:00 UTC onwards) in which holding occurred throughout 2019. Summing these gives the total holding minutes that could be saved for flights that hold.

In addition, it is assumed that a reduction in holding time will reduce queue lengths, leading to a reduction in the number of flights holding. The introduction of eTBS at Heathrow delivered a theoretical 1.1 movements per hour and resulted in a 13% reduction in the proportion of flights holding. It is assumed that the reduction in the number of flights holding at Heathrow under PWS can be estimated as a direct proportion of that the benefit observed for eTBS i.e. PWS will deliver a 5.2% reduction in the number of flights holding because $\frac{0.44}{1.1} \times 13\% = 5.2\%$. The estimated reduction in the number of flights holding is multiplied by the number of arrivals in 2019 (238,818) and the average holding time per arrival flight (3.32 minutes) to estimate the number of minutes holding saved by reducing the number of flights in the stacks.

Combining the two values gives the total holding minutes that could have been saved for 2019, which can then be converted to fuel savings on the assumption that the average fuel burn per minute of holding is 63.8kg/min across all Heathrow arrivals (based on airborne holding at FL80 and a typical Heathrow aircraft fleet mix).

Table 23 shows the estimated fuel and CO₂ savings due to PWS implementation.

	Average
Total Holding Saved in 2019 (minutes)	55,534
Average Holding Saving Per Flight (seconds)	14
Holding Fuel Saved per flight (kg)	14.84
Holding CO₂ Saving per flight (kg)	46.73

Total Fuel Saving in 2019 (Tonnes)	3,543
Total CO₂ Saving in 2019 (Tonnes)	11,161

Table 23: Summary of Fuel and CO₂ findings

A.3.2.4 EXE-OBJ-VLD-03-001C-HP Results

For Human Performance related objectives, please refer to the HPAR [43] for a description of the findings.

A.3.2.5 EXE-OBJ-VLD-03-001C-SAF Results

Introduction

The scope of the Safety assessment covers the assurance evidence output from the Real Time Simulation (RTS) exercise activities on the IA PWS solution using Heathrow airport approach as the representative operation. Controller surveys and feedback were used to assess the operation from a Safety point of view.

Safety Criteria (SAC) define the acceptable level of safety (i.e. accident and incident risk level) to be achieved by the Solution under assessment, considering the impact on the ATM/ANS functional system and its operation. However, the individual SESAR solutions included the VLD activities have already completed their V3 validations and there was no requirement to re-validate them during this demonstration. Subsequently, the success or failure of the RTS exercise activities were solely based on the ability to meet the safety related Demonstration Objectives and Success Criteria, which are detailed in Section A1.2.

Controller Feedback

This assessment has assessed the safety related questions and has considered the results from the Sector Participants. The questions have not been broken down by run.

Except for three essay-style questions, the questions were in a multiple-choice format with up to three options. Where half or more of the responses from the controller group selected favourable results, the overall status of the question has been marked as OK.

The questions addressed the following three key areas:

- User Interface and Procedures
- Losses of Separation (LoS)
- General Safety Impact

User Interface and Procedures

Status: OK

The purpose of the general safety questions was to assess the controller's views on tool, concept and functionality. Subsequently, the questions focus on the interface and basic procedures (it is noted that there is some overlap with the Human Factors (HF) assessment).

As can be seen in Figure 23 below, the results are overwhelmingly positive. Negative responses are due to the specific scenario not having been seen by a controller.

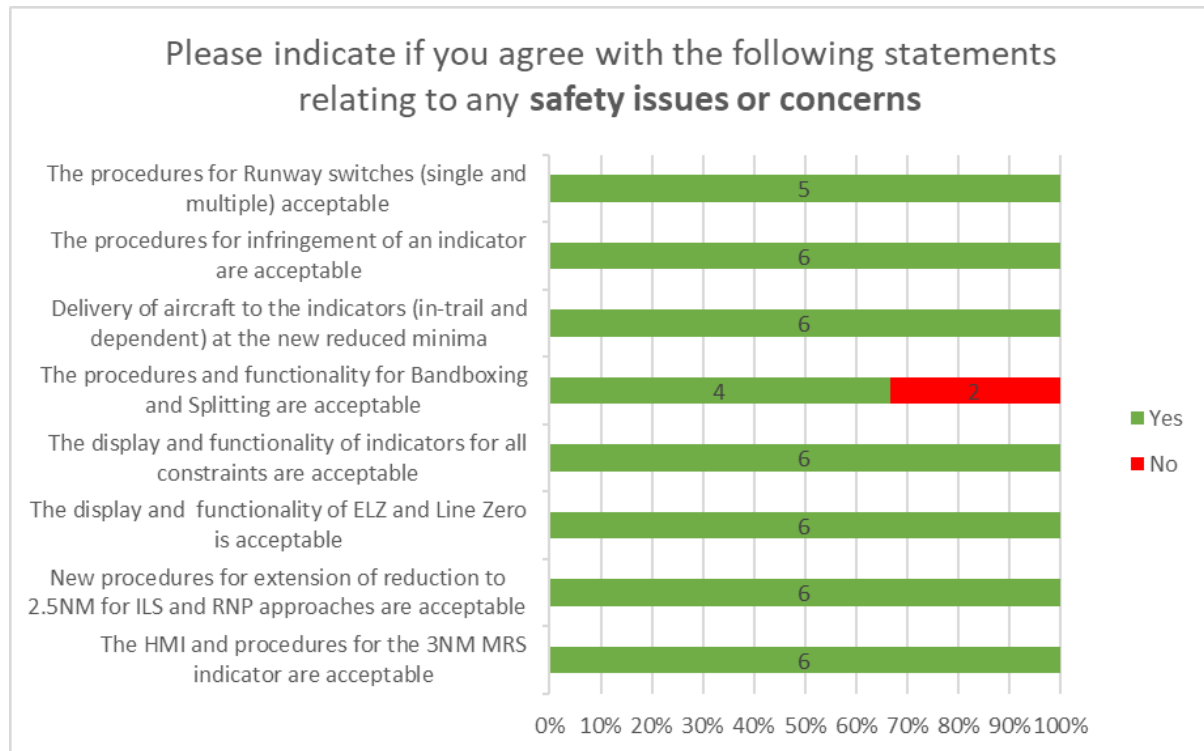


Figure 23: Interface and Procedures

Loss of Separation

Status: OK

The purpose of the questions relating to LoS was to understand how these would be affected compared to the current operation. Therefore, the questions focused on the flight segments where the indicators would be shown, as this is where the concept primarily differs from eTBS.

In general the feedback relating to LoS was positive with no LoS being recorded in relation to the indicator positions. The controller remarks were as follows:

- *I don't recall any losses.*
- *I can't confirm if I did, but I have previously mentioned what I think can happen.*

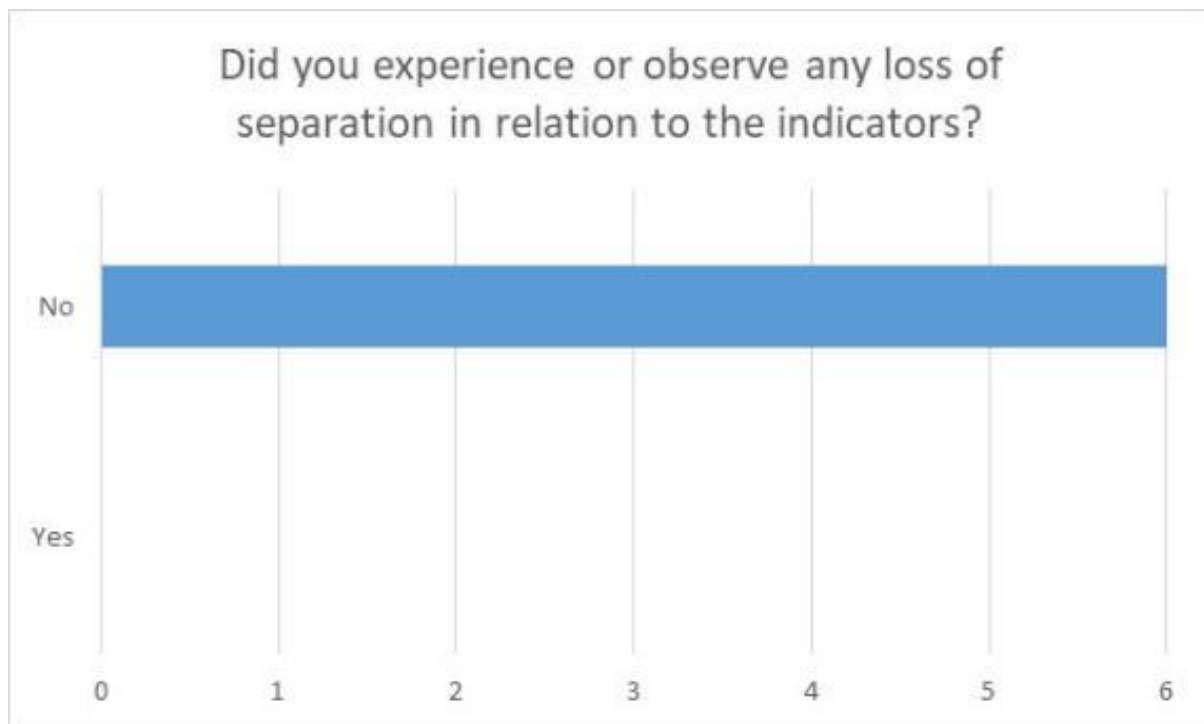


Figure 24: LoS in relation to Indicators

Consecutive Runway Switch

Procedures have been written (in coordination with Safety) for two consecutive switches which will be safety assured. The first aircraft should be switched over, and then when indicator is displayed the second aircraft would be switched over while still applying the rules for indicator infringement. During the operational scenario days a blocked runway was simulated where consecutive runway switches were tested. Whilst the controllers did not have any negative feedback about the defined procedures for consecutive switches, the scenario did raise discussions regarding the infringement procedures when an aircraft is 0.5NM ahead of an indicator and requires breaking off the approach (refer to Section 0.1).

Potential Increase of LoS

When asked whether the concept would increase the number of LoS the results were mostly positive.

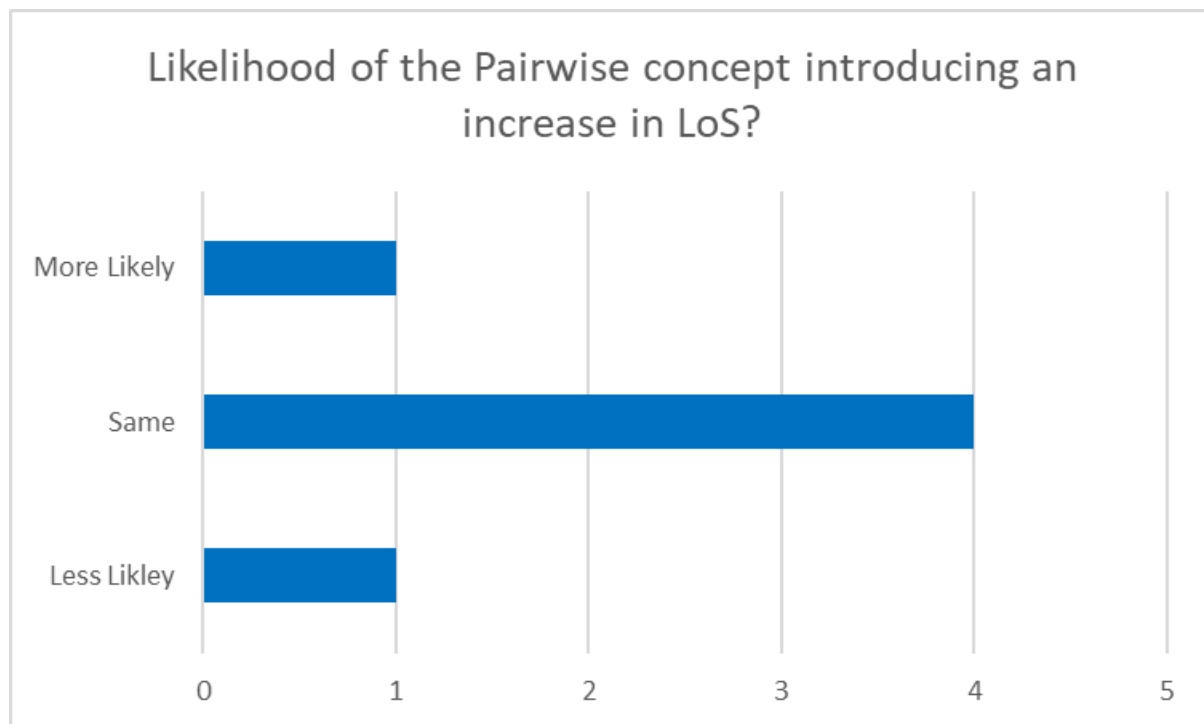


Figure 25: Likelihood of LoS

The controller remarks were as follows:

- *Indicators for MRS. We don't have in today's operation.*
- *I think it is a safe system but the fact we are trying to get aircraft as close of possible means in my opinion, it will not be (stet) more or less safe.*
- *Fine.*
- *I can't see a change based on following the procedures and ATCOs continuing to operate with the fundamentals of separation in mind.*
- *Previously mentioned.*
- *Potential for controllers to utilise bolder base legs when they are trying to achieve <3 mile spacing.*

The questions above addressed LoS during Pairwise operations using the new MRS rules only.

As detailed in Section 0.2 of this document (Delivery of Aircraft to Separation Minima) there were 11 technical LoS during the eTBS runs while there were 0 technical LoS in the PWS runs.

Through expert judgement, it was identified that in all but one case of the eTBS losses, the event would not have triggered a loss under the new Pairwise MRS procedures if aircraft had been positioned in the same way. Based on this analysis, it can be determined that the delivery of aircraft to separation minima is acceptable under the Pairwise solution.

General Safety Impact

Status: OK

The remaining questions were open-ended to attempted to explore any aspect of the design that the controller may perceive to be potentially safety related.

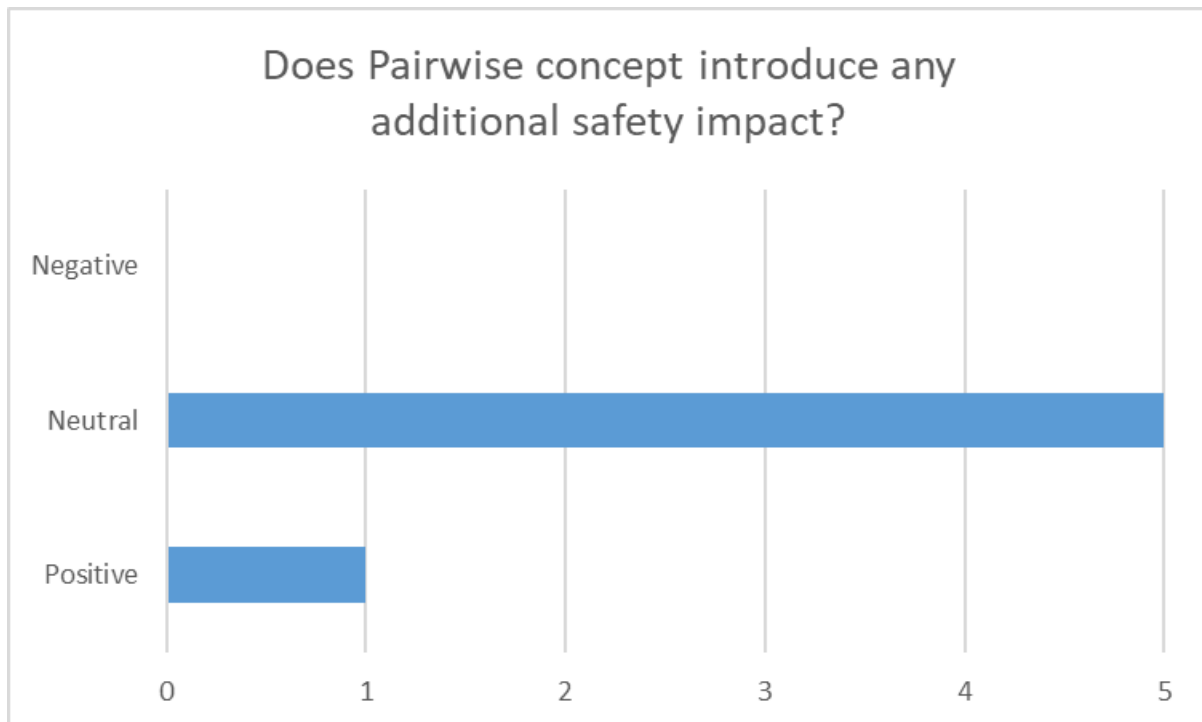


Figure 26: Safety Impact

There was no negative feedback with regards to the general safety impact question.

Remarks were as follows:

- *Guaranteeing 2nm to threshold, MRS*
- *indicators outside 20nm*
- *I think it is as safe as things now.*
- *Fine*
- *I'm not sure the sim environment is a perfect reflection of real life. I couldn't answer until see in real world.*
- *See previous about loss of 2.5nm*
- *Has the potential to reduce safety incidents because the indicator allows you to acquire the suitability of your base leg more quickly with the pairs of aircraft that are close to MRS.*

The following essay style questions were asked regarding General potential Safety Impact:

Question	Results
Based on your operational experience, are there any specific scenarios where safety could be compromised using Pairwise?	All six controllers answered 'No'
Are there any additional changes required to ATC procedures that could improve safety?	Two controllers answered 'No' Remarks were as follows: <i>A thorough training package.</i> <i>Speed control awareness to airlines.</i> <i>Not procedural but needs to be covered in training</i> <i>Perhaps the INTs descending aircraft to 5000ft only to allow FIN to play around with the levels more.</i>
Are there any unusual/infrequent scenarios where a failure of the tool could have a negative safety impact?	Two controllers answered 'No' Remarks were as follows: <i>Potential outliers. But my understanding is that many have been discussed and captured in CONOPS.</i> <i>Other than INT vectoring an aircraft onto the localiser and keeping the strip. Potential for inaccurate line 0 information in this scenario.</i>

Table 24: General Safety Impact - Responses

Note: The safety questions did not explicitly ask for the number of missed approaches during the RTS for the purpose of comparing it to real Heathrow operations. The reason for this is that missed approaches in the current operation may be driven by a multitude of factors that cannot be realistically simulated, such as slow traffic vacating the runway and unstable approaches. Instead, the approach that was taken to meet the safety criteria CRT-VLD-03-001C-SAF-001 was to ask the controllers if they believed the number infrequent/abnormal scenarios would increase because of the use of the IA PWS concept, and then subsequently asking them to elaborate on this issue. There were no controller reports that suggested that missed approaches/go arounds would be affected.

Overall Suitability of the SESAR Solution(s) for Deployment

The ATCOs confirmed that the level of safety during the demonstration was acceptable with no significant issues being reported. As shown in Section A.3.1, all success criteria relating to Safety have been met.

A.3.2.6 EXE-OBJ-VLD-03-001C-SEC Results

In parallel to the validation process, NATS experts have undertaken a Security Risk Assessment on all changes being introduced as part of the Heathrow Pairwise concept. This is in accordance with NATS' internal processes but is aligned with the SESAR methodology. As part of this, Security Risk Treatments were also applied. In line with SESAR guidance, the detailed content of this assessment will not be provided as part of the data pack for sensitivity reasons.

A.3.3 Unexpected Behaviours/Results

The following unexpected behaviours occurred during the demonstration;

- ExCDS and IA software issues as detailed in section A.2, resulted in the controllers unable to use the ExCDS functionality as intended therefore impacting Human performance data collection and analysis, and feedback regarding overall user acceptability of the system.
- An issue was noted with several aircraft during some of the solution runs where certain aircraft were losing code callsign conversion during the exercise. This loss of this information results in the IA tool not recognising the aircraft and therefore the indicator of the aircraft behind is based on the incorrect aircraft. In this scenario, the controller must revert back to using RECAT-EU separation with the addition of 1 NM. As this scenario did not occur in the matched baseline runs, the capacity analysis was required to discount these aircraft pairs from both sets of data.
- During the solution runs, the controllers commented that the indicators seemed to be 'pulling away' once the lead aircraft passed 4DME (i.e., the distance between the follower aircraft to their indicator increased when the lead aircraft passed 4DME). It is likely that this observed issue is caused by the aircraft speed performance modelling in the simulator. Therefore, it is recommended that a review of the sim performance inside 4DME is conducted to ensure that it is consistent with operational data.
- With regards to the runway throughput results, it was expected that a greater benefit would have been seen with Pairwise compared to eTBS with the moderate wind sample. It is unclear to why this result was seen in the analysis. Future revision of the system adaptation may result in additional benefits.
- The data analysis also showed a greater number of aircraft ahead of the indicator (-0.1 - -0.5) at 4DME with Pairwise than eTBS which was unexpected. This is explained because system limitations required the first aircraft in the sample to land before the eTBS tool or Pairwise tool was activated. By this point, under both scenarios, participants had already positioned a stream of aircraft on the final approach behind this first aircraft. There were instances where participants found that the aircraft infringed their indicators when they appeared. As far fewer indicators are provided by the eTBS tool, far fewer instances of this were recorded under the reference scenario.

A.3.4 Confidence in the Demonstration Results

A.3.4.1 Level of significance/limitations of Demonstration Exercise Results

The Demonstration is a simulation that is using early versions of the deployment software for the solution scenario. As these versions of software are pre-FAT and pre-verification, there were issues that were experienced throughout the simulation that impacted the assessment of the user acceptance of system in use and the collection of human performance data.

The simulation was conducted on Heathrow Approach positions only and did not contain simulation capability for the Tower Controllers to take part as a measured position. However, there were Heathrow Tower controllers in attendance at the simulation and they were provided with an emulated Tower ATM where they were able to view an emulated view of the Pairwise Tower indicators, be involved in the generation of scenarios requiring coordination between Tower and Approach and give feedback on the concept from a Tower perspective.

Although effort was made to ensure the traffic samples were representative of the traffic loading and fleet mix at various times of the day at Heathrow, and also contain some specific traffic and inbounds to an adjacent airfield, the controllers commented that the runs felt very 'sterile' and did not represent operations in terms of the number of telephone calls and coordinations that the controllers would normally make. Therefore, any feedback with regards to workload should be caveated with such limitations.

Although the simulation was focussed on assessing the suitability of procedures and acceptability of the concept, at the time of the simulation activity, the Pairwise safety assurance work is on-going and not yet complete.

It has been determined that the findings of this validation are applicable to other very large and large airports that are runway capacity-constrained and operate in segregated mode.

A.3.4.2 Quality of Demonstration Exercise Results

Due to the limitations as described in Sections A.2 and A.3.4.1, the results from EXE-VLD-03-001C exercise must be caveated with such limitations. However, the results derived from the demonstration can still be considered of high value due to the following reasons:

- Experienced NATS Heathrow Approach controllers were used who have all had some previous involvement during the concept development stage of the Pairwise project.
- Although there were issues with the ExCDS tool with lag and crashing, the other aspects of the functionality with regards to conducting operational scenarios were working as designed and the controllers were given adequate exposure to the use of indicators for all aircraft pairs, using time-based PWS-RECAT-EU, Pairwise procedures and 2NM MRS on final approach. The controllers feedback indicated overall acceptability of the concept and tools, and would be comfortable for the tool to be implemented into Heathrow operations.

A.3.4.3 Significance of Demonstration Exercises Results

Although the planned experimental design was to control all variables between matched runs, in some instances, the controller was not the same in all positions, due to operational resourcing constraints. Therefore, any comparative assessment results should be caveated as such. Due to this reason as well as the limited number of matched runs conducted (6 x Matched Pairs), there cannot be any statistical significance attributed to the results, and rather should be used as indicative results only.

A.4 Conclusions

A.4.1 High level conclusions

The following conclusions can be provided in relation to the overall acceptability of the Heathrow Pairwise concept:

- The pairwise concept is acceptable to controllers across operational configurations, including different runway configurations and wind conditions;
- Across a range of operational contexts, controllers found HMI and indicator support acceptable. Controllers generally found the system and HMI intuitive and understood system behaviours;

- The reduction of MRS on final approach from 2.5NM to 2NM, and an earlier reduction from 3NM to 2.5NM in the RMA is assessed as acceptable. All responses from controllers were positive, with participants agreeing this support is acceptable for operations;
- All participants agreed that the defined procedures are acceptable, as defined in the MOps. Comments from controllers suggest that the alignment of new procedures with those pre-established in eTBS operations increases their acceptability;
- The Pairwise concept is acceptable to controllers in cases of broken off approaches, speed non-conformance and missing wake category scenarios;
- Controllers agreed that Early Line Zero is acceptable. The ELZ is seen as a benefit to the operation and useful as information to support the controller which improves predictability.

A.4.2 Conclusions on Key Performance Areas (KPs)

Further conclusions can be drawn with respect to the performance benefits:

- The Pairwise concept supports an increase in arrival throughput in the Heathrow environment. This benefit is heavily influenced by the wind conditions and the individual controller's delivery relative to the displayed indicator. Larger data sets are required to provide a full understanding of the long-term capacity benefits;
- The updated MRS rules decrease the proportion of MRS constrained aircraft pairs at threshold in the traffic sequence. MRS pairs are only present under Pairwise operations in strong wind conditions, where the wake and ROT constraints are reduced.
- For the same traffic sequence, fuel and CO₂ savings can be expected with the implementation of the Heathrow Pairwise concept.

A.4.3 Conclusions on Focus Areas (FAs)

Further conclusions can be drawn with respect to the transversal areas:

Human Factors

From a Human Performance perspective, the overall conclusion drawn from the evidence gathered is that the concept is feasible but requires further refinements being made to some components of the ATM system (i.e., technology, system design and people) and reassessing the impact on HP to improve confidence that the results are accurate and reliable.

Safety

The overall findings of the safety assessment are positive, with no major safety issues having been identified. Furthermore, all Demonstration Success Criteria relating to Safety have been met.

A.5 Recommendations

A.5.1 Recommendations for industrialisation and deployment

A.5.1.1 Recommendations for concept development

- The 'pulling away' phenomenon experienced by participants where the indicator moved ahead of the aircraft once its speed had been stabilised is recommended to be investigated to confirm

whether this was prompted by the simulation performance within 4DME not being consistent with operational data or in fact a tool calibration issue.

- The participant suggestion to avoid 2.5 MRS losses by introducing a standardised drop to a higher altitude than used in the current operation to give the final approach controller the option to use vertical separation should be explored by the concept team to determine the potential inclusion of this procedure in the ConOps.
- The functionality of the Status Spacing Window interface is recommended to reviewed prior to the final validation of the concept to ensure that the presented information reliably gains the controller's attention, when needed.
- Tool behaviour in any unusual/edge-case scenarios are highlighted in controller training and in the CONOPs.
- The next phase of development should review the relevance of the spacing information displayed for dependant aircraft pairs and of the indicator HMI and display for aircraft outside 20 miles from the threshold.

A.5.1.2 Recommendations for future validation

- Conduct further validation activities on the final deployment IA and ExCDS software builds, including final deployment adaptation, to ensure thorough user validation is conducted with all aspects of the functionality working as designed.
- The scale of the final validation activities should be such that a greater number of matched runs in each combination of wind sample and traffic mix can be performed. A larger data set would add further confidence to the performance benefit findings.
- For the formal validation simulations conduct a review of aircraft speed performance modelling inside 4DME in the simulator is to ensure that it is consistent with operational data.
- Conduct validation with users who have not been involved in the development of the concept prior, to ensure a balanced view is obtained.
- Ensure a list of scenarios (particularly all edge case scenarios for IA tool behaviour) that are required to be covered and highlighted in ATC training is compiled.
- Additional HP assessment is recommended to correct for unrealistic ExCDS input/non-ATCO matches.
- The next phase of development should further investigate the validity of the perception that the HMI design of the tools and the operating techniques/procedures associated with the tools increase controllers' workload and whether than increase is acceptable (i.e. falls within the normal variability of workload levels).
- The next phase of development should assess the validity of the perception that more than 0.5nm would be safer for breakthrough.
- The next phase of development should also collect HP data from ATCOs without previous knowledge of or interaction with the concept tools

- SESAR should consider investigating the effectiveness of humans as fallbacks when technology systems fail.

A.5.2 Recommendations on regulation and standardisation initiatives

NATS will be engaging with the UK CAA to obtain the required regulatory assurance to deploy all related updates to separation standards into Heathrow operations. There are no recommendations to include at this stage.

Appendix B Demonstration Exercise EXE-VLD-03-002 Report

B.1 Summary of the Demonstration Exercise EXE-VLD-03-002 Plan

As described in the DEMOP Very Large Demonstrator (VLD) project SESAR2020 VLD3 Wave 2 SORT the exercise EXE-VLD-03-002 aims to industrialize the plate line concept into a prototype of the plate and its installation, which is suitable for permanent deployment and ready for approval by authorities.

B.1.1 Exercise description and scope

The highest risk of aircraft encountering wake vortices prevails during final approach in ground proximity, where the vortices cannot descend below the aircraft glide path but tend to rebound from the ground surface. This is aggravated by the fact that the opportunity for the pilot to recover from a vortex encounter is limited by the low flight altitude. To reduce the risk of wake vortex encounters and potentially reduce aircraft separation minima, a wake decay enhancing device called “plate lines” has been developed and validated to technology readiness level TRL 6 (technology demonstrated in relevant environment) with respect to safety aspects in SESAR2020 WAVE-1 PJ.02-01-07. An experimental installation of plate lines at the approach end of the runway 16 of Vienna international airport has proven to reduce the lifetime of the longest-lived and thus potentially most hazardous wake vortices in the critical height range before touchdown.

The objective of this demonstration is to industrialize the plate line concept into a prototype of the plate and its installation, which is suitable for permanent deployment and ready for approval by authorities. Thus, the concept (solution PJ.02-01-07) will aim at technology readiness level TRL 7 (system prototype demonstration in operational environment) at the end of VLD3-W2-SORT, enabling deployment by airports interested in increasing aviation safety by reducing the number of encounters during final approach. The measurement data collected at Vienna airport will be thoroughly analysed regarding effects of headwind strength, turbulence intensity, and aircraft types on the reduction of wake vortex lifetime and circulation strength. Further, the achievable reductions of separation minima employing the rationale developed for RECAT-EU and RECAT2-EU (static pairwise separations) as well as for dynamic pairwise separations shall be assessed. However, it is not intended to develop a new operational solution supporting reduced aircraft separations. The exercise is structured by the following activities:

1. Elaborate a technical plate line design as well as the design for its installation for permanent deployment at an airport
2. Prepare all material for authority approval like expert opinions on statics etc. needed to receive the approval from the authorities for the installation of plate lines at an airport location
3. Installation of the plate prototype in a suitable environment, e.g. at Vienna airport considering legal, and stakeholders’ requirements
4. Thorough quantification of the acceleration of wake vortex decay by plate lines based on the validation results stemming from WAVE-1
5. Assessment of achievable reductions of separation minima

6. Conducting a demonstration/visitor's day in order to demonstrate that all required qualifications for the installation of plate lines at airports have been fulfilled within VLD3

B.1.2 Summary of Demonstration Exercise #01 Demonstration Objectives and success criteria

The primary objectives are to demonstrate the safety gains that can be achieved by the installation of plate lines (solution PJ.02-01-07) in terms of reduced lifetime and vortex strength (circulation) together with a design for the installation of the plates at the runway ends of an international airport together with all material needed for approval by the authorities and the installation of a plate prototype in an appropriate environment. The solution aims at reaching TRL7 by the end of VLD3-W2-SORT. The compliance with these targets will enable to install plate lines at major airports and to exploit the related safety gains. Additionally, the achievable reductions of separation minima employing the rationale developed for RECAT-EU and RECAT2-EU (static pairwise separations) as well as for dynamic pairwise separations shall be assessed. The question how the estimated reduced separations could be integrated into the RECAT systems and the related safety case are not subject of the current VLD3-W2-SORT and will have to be brought forward in a subsequent project. So, it is not intended to develop a new operational solution supporting reduced aircraft separations.

B.1.3 Summary of Validation Exercise #01 Demonstration scenarios

The reference scenario consists of the regular air traffic approaching runway 16 of Vienna International airport in the time frame ranging from 6 May 2019 to 28 November 2019. During 45 days of landing operations wake vortices were tracked with three lidars in five different observation planes. Relevant data of the landing aircraft has been made available via the Mode-S protocol. The meteorological conditions were monitored employing a comprehensive suite of meteorological instrumentation. The collected data serves as reference characterizing wake vortex transport and decay during a variety of meteorological conditions and for various aircraft types at a major international airport without the effects of plate lines.

The solution scenario consists of the same traffic situation and measurement instrumentation as described by the reference scenario. But in the solution scenario two plate lines are deployed underneath the approach path to runway 16 that interfere with the generated wake vortices and accelerate their decay. The comparison of the wake vortex behaviour with and without plate lines is used to assess the safety gains achieved by the accelerated wake vortex decay in the final approach area. Further, potential capacity gains are assessed by applying the rationale developed for RECAT-EU to the measured wake vortex evolution data measured by lidar. Further, the separation reduction potential of pairwise dynamic (weather dependent) separations will be assessed employing DLR's wake vortex advisory system.

B.1.4 Summary of Demonstration Exercise #01 Demonstration Assumptions

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-002-001	representativity	representativity	overall scenario at Vienna airport is considered representative for other major airports	wake vortex behaviour in ground proximity is controlled by aircraft types, surface roughness and wind conditions which are similar for other airports	medium
ASS-VLD-03-002-002	Statistical significance	Statistical significance	data suffices for robust assessment of qualification of plate lines to accelerate wake vortex decay	more than 1200 vortex pair evolutions were carefully chosen from the data base and processed with high quality	high
ASS-VLD-03-002-003	Statistical significance	Statistical significance	measurement results are suitable to follow the rationale developed for RECAT-EU	reasonable worst-case conditions were chosen such that long-lived vortices were collected which were processed with high quality	medium

Table 25: Demonstration Assumptions overview

It is assumed that the overall scenario at runway 16 of Vienna airport is representative for other runway situations at major airports. This assumption appears appropriate because wake vortex behaviour in ground proximity is controlled by aircraft types, surface roughness and wind conditions which are similar for other airports.

Further, it is assumed that the measurement statistics suffices for robust assessment of the qualification of the plate lines to accelerate wake vortex decay. It is also assumed that the measurement results are suitable to follow the rationale developed for RECAT-EU and RECAT2-EU with respect to the wake vortex generation altitude, the analysed aircraft types and the amount of the processed wake vortex evolutions measured by lidar. These assumptions appear justified because measurement days with reasonable worst-case conditions were chosen such that a comprehensive data base (more than 1200 vortex pair evolutions) of long-lived vortices could be established which has been processed with good quality.

B.2 Deviation from the planned activities

The original plan to receive the approval for the installation of a plate prototype at Vienna airport could not be achieved as the authorities (BMK, Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology) did not support the approval of the installation of a single plate in the vicinity of the runway, without the beneficial effects of reducing the lifetimes of wake vortices generated by landing aircraft. Alternatively, Austro Control considered the installation of a complete plate line, which however could not be realized due to the strongly reduced air traffic given the covid pandemic. In order to largely achieve the original goals of WP3, Austro Control tried to convince the authorities to grant the approvability of a plate line installation (eight plates) at Vienna airport, without actually installing all 8 plates at the end of the runway. This adjusted approach would have facilitated the installation of a plate line once the traffic demand has sufficiently recovered. Unfortunately, the BMK also refused this solution path.

So, a mitigation plan (D3.1.02) has been established describing the impact on WP3 in terms of tasks, outcome, high-level objectives, timing, resources, effort and budget. The main deviations are that the wake decay platform was not installed at the airport but at the antenna test centre Rauchenwarth close to Vienna airport. Further, the full documentation needed for authority approval of the plate installation was compiled however without the authority approval itself. This explicitly includes the external expert opinion regarding the plate design which is basically requested by the BMK. Correspondingly, also Milestone MS5 “Approval of National Authorities received on WP3 platform use” could not be achieved.

Additionally, another prototype plate will be erected on DLR premises in Oberpfaffenhofen next to the Institute of Atmospheric Physics in March or April 2023. The plate prototype will not only serve as a demonstration model for interested stakeholders, but also demonstrate how resistant the design is with respect to weather influences and particularly heavy storms. Such a demonstration will likely help to convince airport decision makers to install plate lines in the future.

B.3 Recommendations

B.3.1 Recommendations for industrialization and deployment

A number of European airports and the respective ANSPs have been approached to conduct an exchange with respect to the airports’ needs regarding wake vortex risks and runway capacity. The goal was to find out whether the airports and ANSPs are interested to install plate lines, on which facts such a decision is based and what further development is needed to make plate line installation an attractive asset.

It became clear that mere safety gains consisting of a reduction of wake vortex encounters in ground proximity and resulting go-arounds do not yet justify an investment in the installation of a plate line as the current situation is considered sufficiently safe. However, for congested airports it would be attractive to install a plate line if the landing capacity could be increased. Five use cases were established which need to be further developed.

- Use Case I. Reduced wake-vortex lifetime will reduce encounter frequency corresponding to an improved safety performance. The reduced encounter frequency will reduce the go-around rates, leading to positive impacts on fuel efficiency, resilience and capacity.
- Use Case II. The introduction of the RECAT-EU scheme or the RECAT-EU-PWS (PairWise Separation) scheme together with the installation of plate lines may advance both, runway throughput for arrivals (three or five additional landings per hour during peak demand) and safety in terms of the wake vortex encounter risks. The PWS scheme requires the installation of some controller support like the separation delivery tool LORD (Landing with Optimum Runway Delivery) developed by EUROCONTROL.
- Use Case III. On top of use case II additional capacity gains of up to two additional landings per hour during peak demand can be made accessible by translating accelerated wake vortex decay into reduced separations following the methods developed for RECAT-EU and RECAT-EU-PWS. As the plates reduce wake vortex lifetime only in ground proximity, it is required to demonstrate that the aircraft separations are still safe along the glide slope. The determined minimum separations along the glide slope reduce the expected capacity gains mainly for RECAT-EU while for RECAT-EU-PWS only a few leading aircraft types restrict some of the aircraft combinations.
- Use Case IV. The application range of the REDSEP method developed for airport Vienna may be extended to situations with weak winds. REDSEP can also be applied at other airports.
- Use Case V. On top of use cases I to IV aircraft separation may be reduced tactically depending on the prevailing weather conditions and the resulting wake vortex behaviour. The delivery of pairwise dynamic separations (RECAT III) requires monitoring and prediction of weather conditions along the glide path. The conducted analysis shows that plate lines reduce the longest-lived wake vortices in ground proximity that are not blown out of the glide path corridor by crosswinds with a strength below 2 m/s. As such reasonable worst-case conditions occur only in about 2% of the time, the corresponding separation gains for pairwise dynamic separations by plate lines are also quite limited and amount to about 2%

B.3.2 Recommendations on regulation and standardisation initiatives

In order to develop a safety case for one of the use cases III to V it would be needed to provide measurements for more heavy vortex generators and to clearly show which area of the final approach is sufficiently covered by the beneficial plate line effects.

Appendix C Demonstration Exercise EXE-VLD-03-004 Report

C.1 Summary of the Demonstration Exercise #01 Plan

This section covers the VLD for WP5, addressing improvements for Airport operator, Airspace users and ATC at Stockholm-Arlanda Airport.

Integrated Runway Sequence Function (IRSF) has earlier in SESAR ER projects (PJ 02.08) been validated through a series of activities including real time simulations and fast time simulations.

There is a need to increase runway capacity in order to meet the high future demand at large airports such as Stockholm-Arlanda. IRSF can bring benefits such as improved runway capacity, predictability, fuel efficiency and reduced environmental impact. By using IRSF to achieve early and dynamic planning for arrival and departure sequences the efficiency of the runway usage can be improved.

Stockholm-Arlanda Airport Runway layout is shown in the picture below. For this exercise 19R and 19L runways has been used. The distance between the parallel runways is 2 300 m. Thresholds of runway 19R (3 300 m) and 19L (2 500 m) are staggered by 1 600 m.

Runway 08/26 have dependencies with flights operating on the other runways. The airport layout, seen in Figure 26, is representative for a large number of airports, including when operating on parallel runways, dependent runways, and also on a single runway. Integration of arrival and departure flights can be managed in all these runway configurations by IRSF.



Figure 27: Stockholm-Arlanda runways

C.1.1 Exercise description and scope

The demonstration has been performed on three different locations. Stockholm ATCC (conference room), Arlanda tower (conference room) and Malmö ATCC (simulator room). See example in Figure 27.

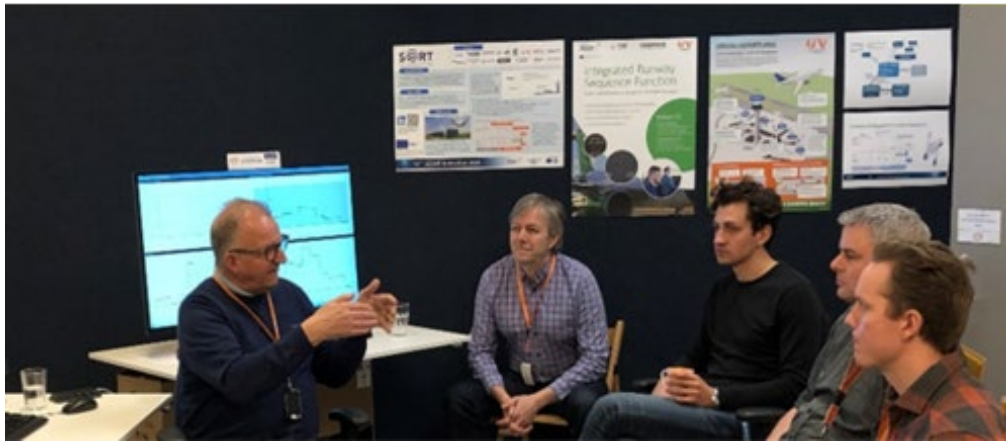


Figure 28: VLD-03-004 demo for ATCOs at ATCC Stockholm

- The demonstration in Stockholm ATCC building included live and recorded data.
- The demonstration in Arlanda tower building included recorded data.
- The demonstration in Malmö ATCC building included live and recorded data as well as a technical explanation of the system.

The scope of the VLD is to demonstrate improvements connected to OI Step TS-0301, focusing on optimizing runway throughput, and TS-0313, focusing on capacity optimization and predictability on airport operations. The following KPA was looked at during demonstrations:

- CAP KPA: Increase **RWY capacity**, by optimising the spacing between arrivals and departures in all situations in a dynamic way; and also, by balancing between the runways in parallel, mixed mode, when applicable.
- PRD KPA: Increase **predictability and punctuality** by making all ATS units follow a common plan based on an accurate integrated runway sequence;
- ENV KPA: Increase **fuel efficiency** by reducing overall flight duration (mostly reducing the need for holdings and the overall taxi-time as a result of following an accurate integrated runway sequence). The Integrated Runway Sequence Function can also help to avoid **noise** sensitive areas by suggesting to move flights to another runway.

The demonstration platform consisted of the NARSIM simulator, the Integrated Runway Sequence Function (IRSF) including a set of AMAN functions and the Enhanced DMAN. An overview of the systems connected to and used by IRSF can be seen in Figure 28.

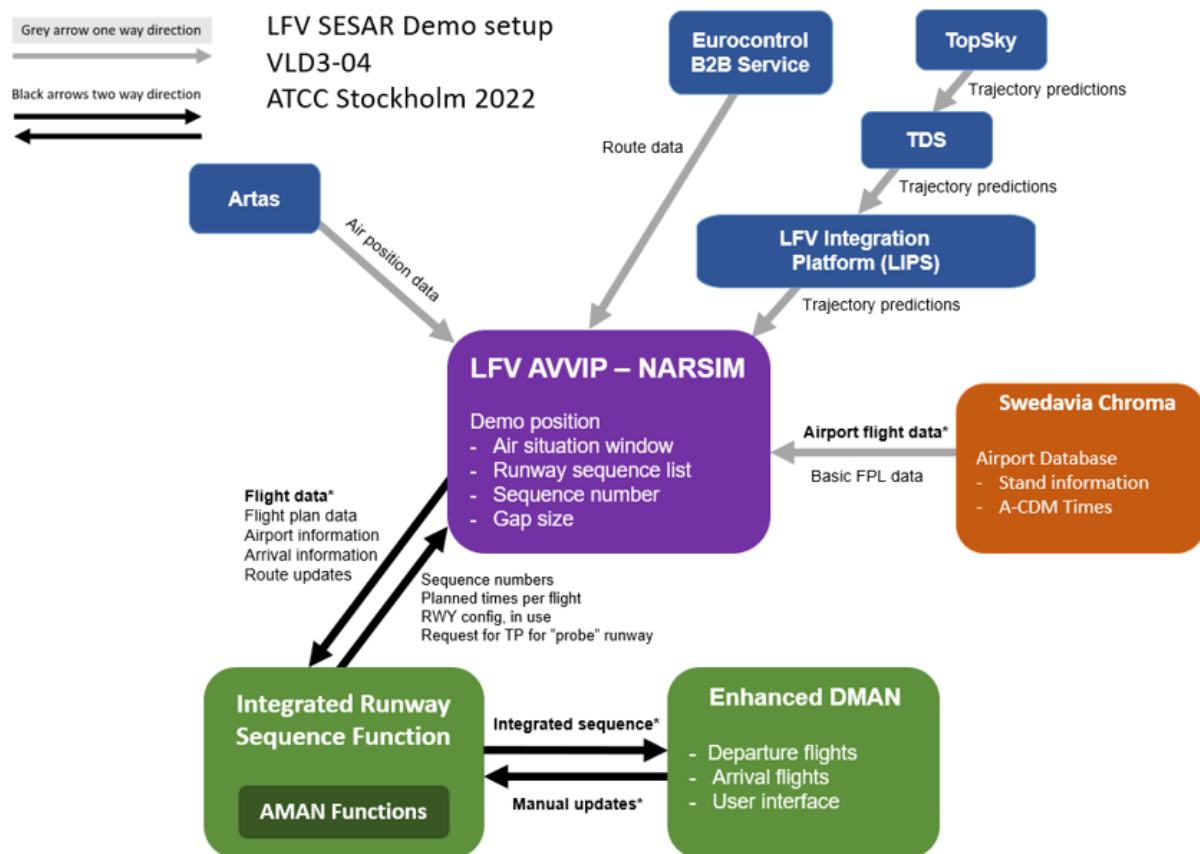


Figure 29: System components integrated with the IRSF

The HMI for IRSF can be seen in Figure 29 and Figure 30, where, to the left in the Figure 29, options for runway block such as snow cleaning and maintenance can be found as well as options for visibility, environment, breaking action etc. The runway block, more specific snow cleaning, can be seen in use in Figure 31. The runway block results in that flights are automatically moved to an appropriate time outside the runway block. When for example visibility is changed, IRSF changes taxi times that are used in order to keep an as realistic taxi profile as possible. These values have been tuned in this project to fit Stockholm-Arlanda, but can be tuned to fit in any airport.

IRSF get updates such as take-offs and landings. This information is automatically updated in the HMI that display at what stage an aircraft is. IRSF are also able to handle RNP AR and a dialogue with SESAR PJ 02.04 has taken place in order to comply in the future with procedures and spacing advisory that is developed in that project. IRSF also supports and improves the turnaround process with early and dynamic planning.

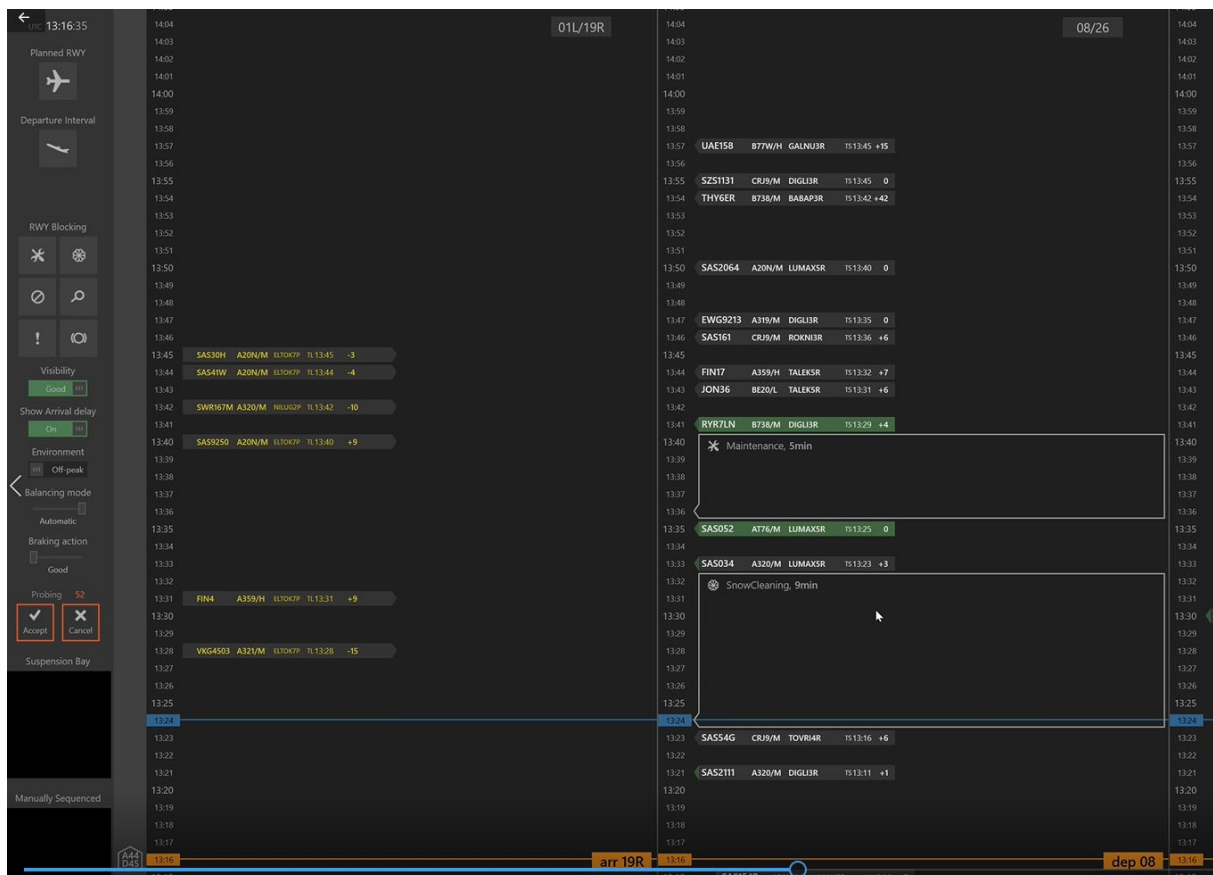


Figure 30: HMI for IRSF / Enhanced DMAN



Figure 31: HMI for mixed mode runway

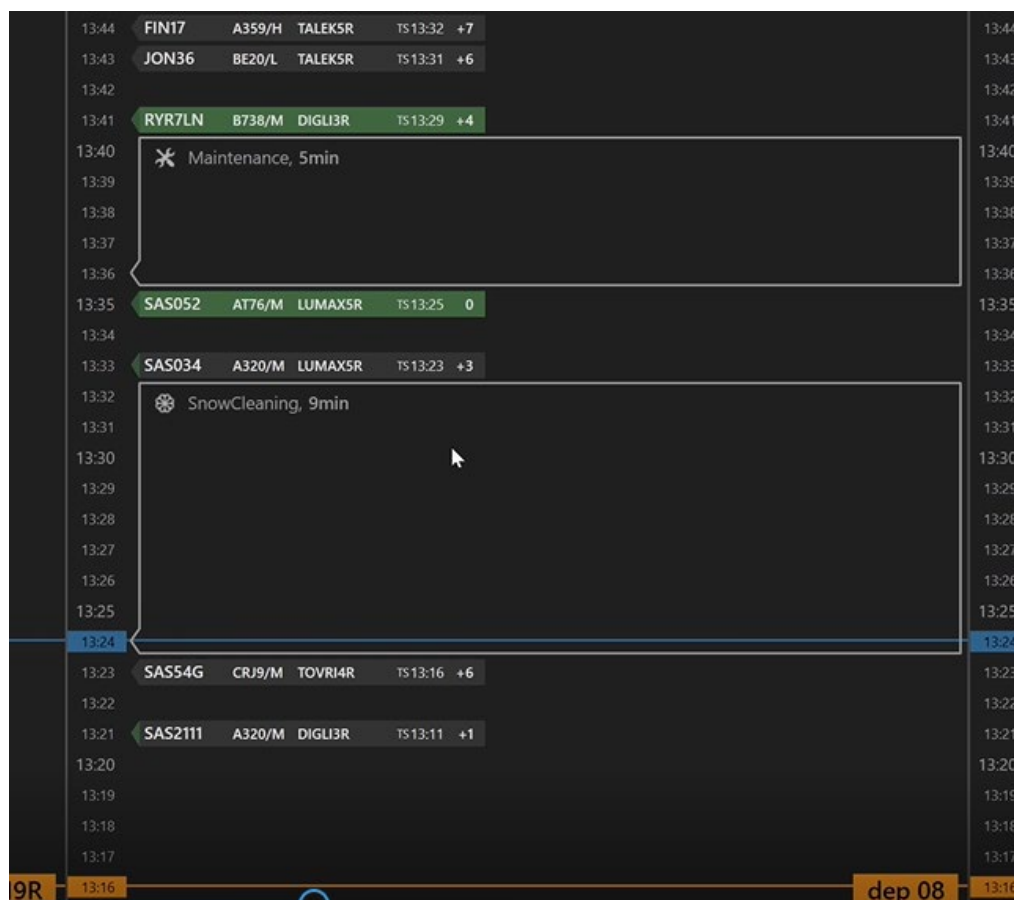


Figure 32: HMI for IRSF / Enhanced DMAN with runway block Snow Cleaning

In Figure 32, the KPI window connected to IRSF can be seen. This is a useful tool to help optimise the usage of IRSF to get a better understanding on how the different settings affects different KPIs. By choosing certain KPIs to work with, an airport can more easily optimise KPIs such as runway capacity or taxi times. The KPI window also gives an overview of when the airport is used to its fullest capacity in order to being able to plan workload in the near future. The KPI window also support probing. This means that if an ATCO uses IRSF and probes a runway change, the HMI will change flights to the new proposed runway, while the KPI window will display the new KPI values. This makes it easier for ATCOs to choose the optimal runway configuration depending on what KPI that is of interest.



Figure 33: IRSF KPI view

C.1.2 Summary of Demonstration Exercise #01 Demonstration Objectives and success criteria

Demonstration Objective	Demonstration Success criteria	Coverage and comments on the coverage of Demonstration objectives	Demonstration Exercise Objectives	Demonstration Exercise Success criteria
OBJ-VLD-03-004-001	CRT-VLD-03-004-001	Full coverage	Capacity: To show potential for increased runway capacity with the use of the Integrated Runway Sequence Function	Potential for increased runway capacity, with at least 5%, with the introduction of the Integrated Runway Sequence Function has been demonstrated
OBJ-VLD-03-004-002	CRT-VLD-03-004-002	Full coverage	Environment: To show potential for decreased departure taxi time with the use of the Integrated Runway Sequence Function	Potential for decreased departure taxi time with the introduction of the Integrated Runway Sequence Function has been demonstrated

Demonstration Objective	Demonstration Success criteria	Coverage and comments on the coverage of Demonstration objectives	Demonstration Exercise Objectives	Demonstration Exercise Success criteria
OBJ-VLD-03-004-003	CRT-VLD-03-004-003	Full coverage	Environment: To show potential for decreased arrival flying time with the use of the Integrated Runway Sequence Function	Potential for decreased arrival flying time, in relation with capacity increase, with the introduction of the Integrated Runway Sequence Function has been demonstrated
OBJ-VLD-03-004-004	CRT-VLD-03-004-004	Full coverage	Environment: To show potential for avoiding noise sensitive area with the use of the Integrated Runway Sequence Function	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated
OBJ-VLD-03-004-005	CRT-VLD-03-004-005	Full coverage	Predictability and Punctuality: To show potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function has been demonstrated

C.1.3 Summary of Validation Exercise #01 Demonstration scenarios

C.1.3.1 Reference Scenario(s)

For the use of trajectory based Integrated Runway Sequence concept, the reference scenario considered is the current situation where AMAN and DMAN separately provide support to the ATCOs. The focus for ATCC Stockholm was AMAN presentation and for ATS Arlanda DMAN presentation.

The demonstration will be performed using live data, and pre-recorded live data, where the real-life events occurring will be used as reference, and the solution will be run in shadow mode, using the same data.

The procedures used at Stockholm – Arlanda are the following:

- The **TWR Runway Controller** manage the arrival and departure flights in order to maximise runway throughput. The arrival sequence is provided by approach (from AMAN) and departure sequence is provided by the ground controller. The integration of both sequences and the planned use of runway occupancy time per flight is done manually by each ATCO and not shared via an HMI with the other stakeholders.
- The **TWR Ground Controller** manages the traffic taking into account arrivals and departures. The departure sequence is developed manually depending on flight progress, wake turbulence and possible use of runway intersection.
- The **TWR Supervisor** performs the role of sequence manager with focus on departure sequence planning, setting and adjusting runway departure rates according to changes, by monitoring the departure sequence and by introducing the necessary manual changes when required. Also oversees the traffic progress and provides real time coordination with the Approach Coordinator.
- The **Approach Controller** manages the arrival and departure flights in the TMA (arrival sequence calculated by the AMAN).
- The **Approach Coordinator** oversees the traffic progress and provides real time coordination with En-route sectors and TWR Controllers. Supports Approach Controllers with information related to sequence management.
- The **TMA Tactical Supervisor** performs the role of sequence manager with focus on arrival sequence planning, setting and adjusting runway landing rates according to changes, by monitoring the arrival sequence and by introducing the necessary manual changes when required.

In this situation, consistency between tools and operating methods are maintained by manual coordination between TWR Supervisor, TMA Tactical Supervisor, Approach Coordinator and APP and TWR Controllers.

More details are provided in the Solution PJ.02-08 OSED for V3.

Note: For the Airport CDM process a Departure Sequencer Tool (DST) is developed by the Airport Operator to provide TTOTs, the system is implemented in TWR but during the VLD demonstrations not in operational use.

C.1.3.2 Solution Scenario(s)

For the use of trajectory based Integrated Runway Sequence, the solution scenario considered is the situation where an Integrated Runway Sequence function establishes an integrated arrival and departure sequence by providing accurate TTOTs and TLDTs, including dynamic balancing of arrivals and departures to optimise runway throughput. There is always a possibility to make manual adjustments, but the integration of arrival and departure sequences will be mostly automated.

The VLD setup will use live traffic data to be used by the Integrated Runway Sequence Function, in order to perform planning of an integrated runway sequence including both arrival and departure

flights. This plan will be updated based on real events and progress of flights, actual landing times and take-off times will provide data to feed the updates into the dynamic integrated plan.

Some live traffic events, e.g. peak traffic events, runway closure, go-around and change of runway in use, will be recorded beforehand to demonstrate and evaluate valuable functionality when using the Integrated Runway Sequence Function.

Using shadow mode in specific situations, with e.g. the runway configuration in segregated mode, (one DEP RWY mainly for departures, one ARR RWY mainly for arrivals) simulator pseudo-pilot functions will be used to demonstrate arrival flight landing on DEP RWY. In this way specific events can be demonstrated and evaluated to study impact on operations and KPAs.

The concept, seen in Figure 33 illustrates the activities in a timeline for arrival- and departure management that results in planned landing and take-off events. The initial runway sequence is set before top of descent in order to allow airspace user to fly at an optimal flight trajectory while also balancing flights between alternative runways. High predictability is achieved by combining early planning with dynamic updates while respecting the operational need of a stable phase.

The main goal for the IRSF is to establish the best possible arrival and departure sequence by providing accurate take-off times and target landing times while also dynamically balance arrivals and departures.

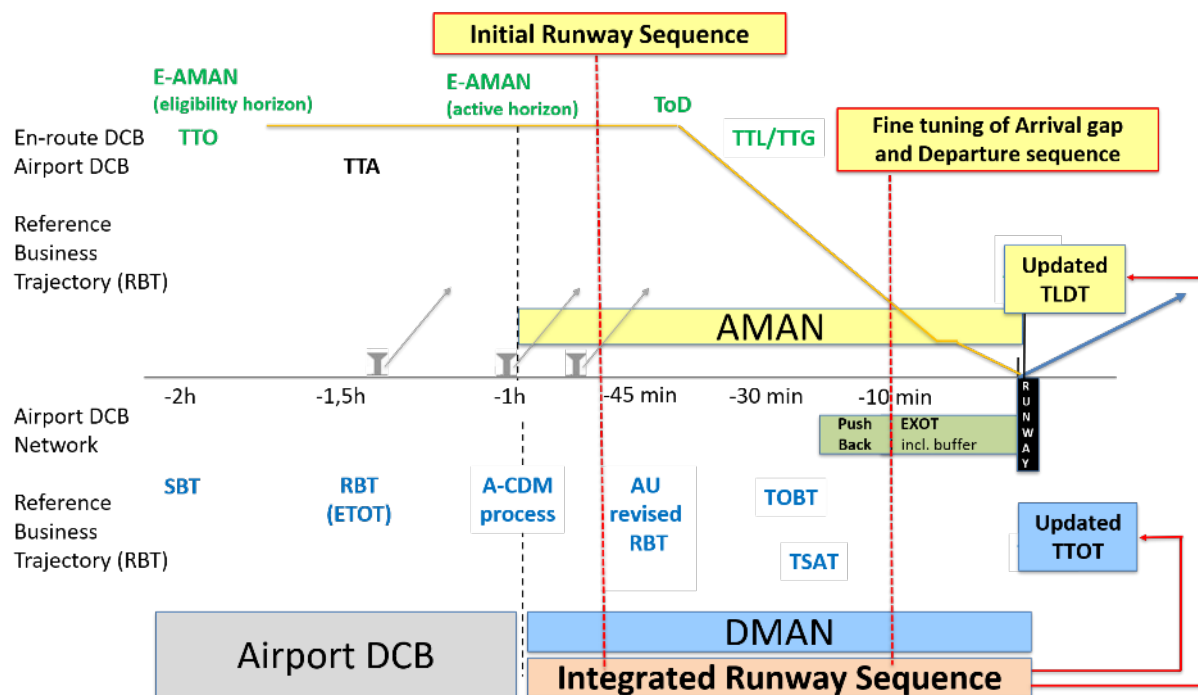


Figure 34: IRSF Concept

The integrated sequence optimization of target landing times and target take-off times is firstly calculated by the IRSF in a look ahead time horizon for balancing of arrivals and departures according to demand. A set of configured parameters can be tuned in order to achieve the best trade-off between efficiency, predictability and optimized throughput.

The following procedures are defined for the concept:

- **Clearance Delivery Controller** will provide start-up approval based on TSAT (in line with local A-CDM preferences). TSAT calculation are based on TOBT and accurate estimated taxi times provided by tabulated values. The Integrated RWY Sequence function will calculate TSAT and TTOT based on live data including updates by monitoring progress of arrival and departure flights.
- The **TWR Ground Controller** will provide push-back approval in line with TSAT. Taxi-out clearance is arranged to meet the proposed departure sequence, updated in line with TTOTs as closely as practical. Handle deviations and possible updates based on remaining taxi-out time with update of departure sequence. Propose the use of runway intersections according to local procedures.
- The **TWR Runway Controller** will verify that the runway is clear and that the aircraft will meet arrival/departure separation requirements. He/she has to respect and follow the departure sequence and TTOTs as closely as practical. In coordination with Flight Crew use runway intersections according to local procedures to maintain runway throughput.
- The **Approach Controllers** will, as long as practical, respect the integrated runway sequence for arrival traffic and provide relevant gaps between arrivals to accommodate departing flights (option to use chevrons when available).
- The **Approach Coordinator** provides tactical coordination, oversees the traffic progress and provides real time coordination with En-route sectors and TWR Controllers. Supports Approach Controllers with information related to integrated runway sequence function.
- The **TMA Tactical Supervisor** provides pre-tactical coordination, performs the role of sequence manager with focus on arrival sequence planning, setting and adjusting runway rates according to changes, by monitoring the integrated runway sequence function and by introducing on it the necessary manual changes when required. Performs coordination with Tower Supervisor on sequence planning based on integrated runway sequence proposal.
- The **TWR Supervisor** performs the role of sequence manager with focus on departure sequence planning, setting and adjusting runway rates according to changes, by monitoring the integrated runway sequence function and by introducing on it the necessary manual changes when required. Performs coordination with TMA Tactical Supervisor on sequence planning based on integrated runway sequence proposal.

More details are provided in the Solution 02-08 OSED for V3.

One controller working position in VLD provided an example with combined set-up for tower, approach and supervisors.

C.1.4 Summary of Demonstration Exercise #01 Demonstration Assumptions

Identifier	Title	Type of Assumption	Description	Justification	Impact on Assessment
ASS-VLD-03-004-001	Traffic level	Other airports	overall scenario at Stockholm-Arlanda airport is considered representative for other major airports	Stockholm-Arlanda airport is seen as a major airport	High
ASS-VLD-03-004-002	Traffic Level	Traffic amount	The traffic at Stockholm – Arlanda is seen as enough in order to obtain data of relevance	Traffic at Stockholm-Arlanda is seen as normal for the size of the airport and can thereby be used in order to obtain relevant data	High

C.2 Deviation from the planned activities

Deviations from the initial DEMOP for WP5 is an extended number of days for demonstration of the system at Swedavia tower building in Stockholm-Arlanda. This due to a high interest in the solution, which lead to the need for an extended demonstration period. This is seen as a positive deviation and did not affect the demonstration or the demonstration plan negative in any way.

C.3 Demonstration WP5 Exercise VLD-03-004 Results

C.3.1 Summary of Demonstration Exercise VLD-03-004 Demonstration Results

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
OBJ-VLD-03-004-001	Capacity: To show potential for increased runway capacity with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-001	Potential for increased runway capacity, with at least 5%, with the introduction of the Integrated Runway Sequence Function has been demonstrated	The capacity can be improved by 12,5% with the introduction of IRSF	OK
OBJ-VLD-03-004-002	Environment: To show potential for decreased departure taxi time with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-002	Potential for decreased departure taxi time with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data for taxi-time improvements has been gathered.	NOK Not available in the technical set-up
OBJ-VLD-03-004-003	Environment: To show potential for decreased arrival flying time with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-003	Potential for decreased arrival flying time, in relation with capacity increase, with the introduction of the Integrated Runway Sequence Function has been demonstrated	Potential to decrease arrival flying time while also increasing runway capacity with the use of IRSF has been demonstrated.	OK
OBJ-VLD-03-004-004	Environment: To show potential for avoiding noise sensitive area with the use of the Integrated Runway Sequence Function	CRT-VLD-03-004-004	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated	The potential to avoid noise sensitive areas has been demonstrated by replanning of arrival flights to land on departing runway or using RNP AR, thereby lowering the noise over noise sensitive areas.	OK

Demonstration Objective ID	Demonstration Exercise Objectives	Demonstration Success criteria ID	Demonstration Exercise Success criteria	Exercise Results	Demonstration Objective Status
OBJ-VLD-03-004-005	Predictability and Punctuality: To show potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function	CRT-VLD-03-004-005	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data regarding predictability and punctuality was gathered with focus on difference in actual and Flight Plan or RBT durations as Flight Plans was not updated with information from the solution. Thereby no reduction in variance of difference in actual and Flight Plan or RBT durations can be presented. Predictability and punctuality was observed to be improved by the system when observations on ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.	NOK Not available in the technical set-up

C.3.1.1 Results per KPA

Capacity

The highest increase of capacity seen in the PJ02-08 V3 validation was 8.4% with an average of 5.1% based on collected data. A calculated value was used during the validations in order to show the potential capacity increase. The calculated values are based on the normal amount of capacity Arlanda handles at peak traffic with what the new amount of capacity could be with the help of IRSF.

The calculated value of how much the capacity could increase with the help of IRSF during the VLD demonstrations were 12.5%.

The traffic amount did, as the demonstrations were based on live data, not reach the same level as during the V3 validation. Thereby could collected data not be compared between the V3 validation and the demonstration.

Efficiency

Allocation of RNP-AR approaches before arrival flight top of descend increase flight efficiency when an optimal flight profile could be used. See Figure 34 below for a RNP AR to runway 19R at Stockholm-Arlanda.

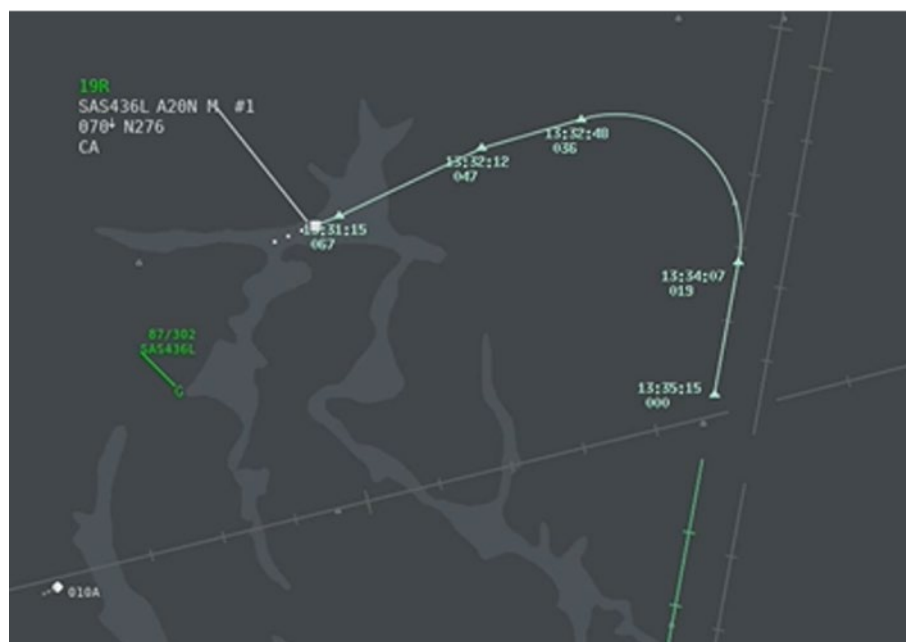


Figure 35: Short RNP AR STAR to runway 19R at Stockholm-Arlanda

During the PJ02-08 V3 validation and the demonstration an overall benefit of fuel burn and CO2 emissions could be identified mostly based on the lowered arrival flight time.

In the V3 validation there was a problem to depart heavy traffic due to gap sizes which affected the taxi times negatively. The gap sizes for the demonstration have been further improved and evaluated with better suitable gap size for heavy traffic and variable taxi time depending on visibility-, surface- and traffic conditions.

Predictability

Increased predictability with an integrated sequence presented before arrival flight top of descent increase ability to plan for landing on departure runway and also use RNP-AR approaches.

IRSF early setting of the integrated sequence was found to increase prediction also for the En-route controllers.

Predictability is seen as just as high for arrival and departing flights during V3 validation and demonstration while it is seen as improved for taxi times in the demonstration as variable taxi time depending on visibility-, surface- and traffic conditions has been added to the system. Additional improvements in the VLD set-up such as presentation of runway sequence in radar label and provide TSAT including planned start/end of de-icing has also to be implemented.

Safety

The IRSF set-up in semi-automatic mode, or in automatic mode, did not propose any hazardous solutions.

C.3.1.2 Results on improvements identified in PJ02-08 V3 RTS

This section cover a number of areas addressed on the PJ02-08 V3 Real Time Simulation in 2019. During the VLD activities operational staff could confirm these operational improvements as valuable.

Mixed mode operations on parallel runways

Today Stockholm-Arlanda Airport has slots up to 84 movements per hour when using runways in segregated mode. The validation of Integrated Runway Sequence, using system support for dynamic balancing when both parallel runways are used in mixed mode, demonstrate option to have slots up to 90 movements per hour. Higher levels of runway throughput can be achieved, depending on traffic mix of arrivals-departures and flights wake turbulence categories.

During the previous V3 real time simulation a capacity increase could be verified with ATCOs working to handle 90 movements per hour, see Run 9 Solution in Figure 35, when using IRSF to enable efficient use of mixed mode flights on the parallel runways.

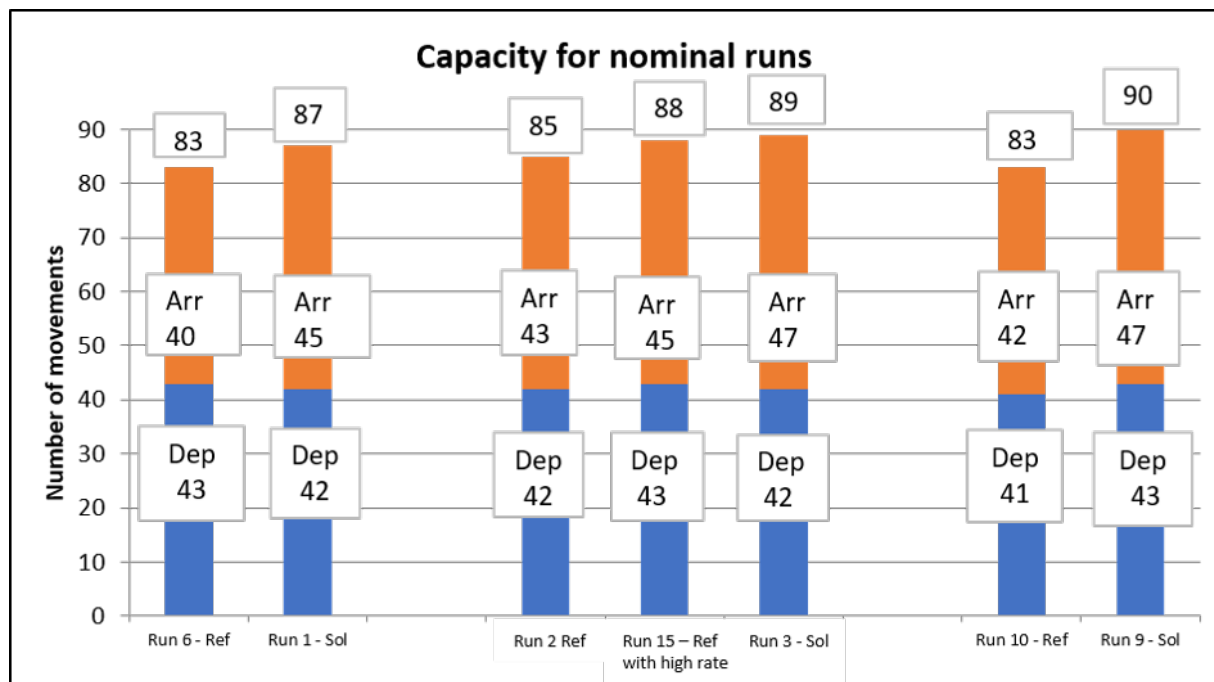


Figure 36: Capacity for nominal runs in PJ02-08 V3 real time simulation.

Results from the VLD demonstrations, with participation of operational staff and aviation experts, confirmed capability for a capacity increase at Stockholm-Arlanda Airport when using both parallel runways in mixed mode, leading to improved environmental sustainability.

Additional entry taxiway – intersection to runway 01L and runway 19R

During the V3 real time simulation a new additional intersection for departures provided increased flexibility to meet the planned sequence in mixed mode operations. See Figure 36. The controllers found the option for a new intersection as very valuable to increase flexibility in which aircraft to depart first, to ensure high runway throughput.



Figure 37: Additional runway entry for 19R compared to 19L design

In the VLD demonstration we received operational feedback to confirm a need for additional runway entry for both 19R and 01L, especially when there is a mix on both arrivals and departures on the same

runway. Runway 01R and 19L can be seen as good examples with multiple intersections to enter the runway, see Figure 37.

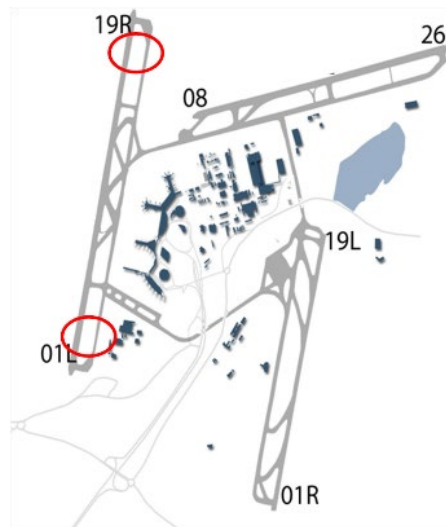


Figure 38: Additional runway entry proposed for 01L and 19R

Ground radar display for approach sectors

During the V3 real time simulation an airport ground radar display was available at APP sectors, see Figure 38. The ATCO experience of this was very positive. They gave the feedback that it reduced the needed coordination and also increased their situational awareness.

In the VLD demonstration ATCOs confirmed the need for presentation of an airport ground radar display at the approach sectors, to improve awareness and operational efficiency.



Figure 39: Approach sector with airport ground radar display in V3 RTS

C.3.1.3 Results impacting regulation and standardisation initiatives

No results indicated a direct need for new regulations or standardisations to be developed and implemented in order for the solution to work in a safe way.

C.3.2 Analysis of Exercises Results per Demonstration objective

OBJ-VLD-03-004-001 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-001	Potential for increased runway capacity, with at least 5%, with the introduction of the Integrated Runway Sequence Function has been demonstrated	The capacity can be improved by 12,5% with the introduction of IRSF	OK

Stockholm-Arlanda Airport can, in the reference scenario, handle around forty arrivals per hour while also being allowed to land five aircraft per hour on the departure runway. This is based on the environmental permit that is active on Stockholm-Arlanda Airport at the time of the demonstrations, when runway configuration with parallel runways used in segregated mode. However, without a tool that allows early planning of sequence it can be hard to get the five landing on the departure runway to fit within the departure sequence. The IRSF, when used in Semi-automatic mode or Automatic mode, will either propose or plan the five landings on the departure runway, thereby optimizing the use of gaps at all times and increase the capacity from forty to forty-five landings per hour. This result in a calculated capacity increase of 12,5%. The results from the V3 validation shows an average runway capacity increase of 5.1%.

IRSF will also optimize sequence in regards to the turbulence category, for example landing heavy flights after another heavy flights in order to minimize and optimize gaps.

The following two statements could further improve the runway capacity:

- If the environmental permit was to be changed so that unlimited number of flights was allowed to land on the departure runway and take-off on the arrival runway, it would allow a free mixed mode operation to be used. This means that IRSF could be able to freely mix arrivals and departures between the different runways, thereby increasing runway capacity.
- The VLD demonstrations was based on live data in order to show how the system would work with real life traffic. However, IRSF are developed to handle more traffic than the amount that was used from live data, thereby the runway capacity can increase to allocate a higher number of flights.

OBJ-VLD-03-004-002 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-002	Potential for decreased departure taxi time with the introduction of the Integrated Runway Sequence Function has been demonstrated	No data for taxi-time improvements has been gathered.	NOK Not available in the technical set-up

The results from the PJ02-08 V3 validation shows slightly longer taxi times compared to the reference scenario, mainly due to problem in departing heavy traffic in their intended gaps. Further development has been done to IRSF and it now allow the user to adjust the traffic situations between peak and off-peak traffic which adjust the departure queue at the runway hold. IRSF will calculate the needed gap between aircrafts for taxi, thereby minimizing the need for long taxi times with holdings and reducing the number of simultaneous taxiing departures. This will also make sure that heavy flights has a big enough taxi gap, making it easier to depart heavy flights.

The time it takes for a flight to taxi from a certain gate to a certain runway has been measured during longer periods of times, thereby ensuring that the gaps used in IRSF are as realistic as possible. The taxi times and gaps are also altered with respect to visibility value, based on how the visibility at the airport is and based on how the surface conditions of the taxiways and runways are at the airport.

All parameters mentioned can be changed in order to further improve and fine tune taxi times and gaps if needed.

No data from the VLD demonstration with focus on taxi times could be gathered. This due to uncertainties regarding taxi time as no ground radar was used during demonstration.

OBJ-VLD-03-004-003 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-003	Potential for decreased arrival flying time, in relation with capacity increase, with the introduction of the Integrated Runway Sequence Function has been demonstrated	Potential to decrease arrival flying time while also increasing runway capacity with the use of IRSF has been demonstrated.	OK

IRSF, when used in Semi-automatic mode or Automatic mode, will either propose or plan five landings on the departure runway. This will lead to a decrease in overall arrival flying time while also increase runway capacity.

With the improved planning from IRSF it will be easier for ATCOs to use RNP AR STAR as these shorter approaches often lowers the arrival flying time and increase the runway capacity.

If the environmental permit was to be changed so that unlimited number of flights was allowed to land on the departure runway and also perform departures on the arrival runway, it would allow a free mixed mode operation to be used. This means that IRSF could be able to freely mix arrivals and departures between the different runways, thereby planning the arrival to the closest runway instead of having to place flights in the queue to a certain arrival runway. This would also both decrease the arrival flying time and increase the runway capacity.

Observations from the demonstration shows that the arrival flying time could be decrease with help from IRSF.

OBJ-VLD-03-004-004 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-004	Potential for avoiding noise sensitive area with the introduction of the Integrated Runway Sequence Function has been demonstrated	The potential to avoid noise sensitive areas has been demonstrated by replanning of arrival flights to land on departing runway or using RNP AR, thereby lowering the noise over noise sensitive areas.	OK

As IRFS improve sequencing and planning on arrival flights, heavier flights can be placed to land on departure runway in order to avoid noise sensitive areas.

An example of this is when 01L is used as departing runway and 01R is used as arrival runway. Arrival flights will fly over a noise sensitive area when landing on 01R. By landing flights on 01L, that is the departing runway, the amount of noise produced over the noise sensitive area can be lowered.

Another example for minimizing the effect on noise sensitive areas are when RNP AR is being used for 01R. This makes the arriving flights to not approach Stockholm-Arlanda Airport over the noise sensitive areas. Thereby minimizing once again the produced noise over the noise sensitive area.

Both these examples need early planning of the sequence in order to be achieved in a safe way.

OBJ-VLD-03-004-005 Results

Criterion ID	Success Criterion	Validation Result	Status
CRT-VLD-03-004-005	Potential for a reduction in variance of difference in actual and Flight Plan or RBT durations with the introduction of the Integrated Runway Sequence	No data regarding predictability and punctuality was gathered with focus on difference in actual and Flight Plan or RBT durations as Flight Plans was not updated with information	NOK Not available in the

Criterion ID	Success Criterion	Validation Result	Status
	Function has been demonstrated	from the solution. Thereby no reduction in variance of difference in actual and Flight Plan or RBT durations can be presented. Predictability and punctuality were observed to be improved by the system when observations on ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.	technical set-up

Results from the PJ02-08 V3 validation shows an average decrease of variation between actual and Flight Plan or RBT duration of 60.8%, thereby improving predictability, similar observations were done during the demonstration for flights that was monitored with IRSF but not altered.

For flights that was altered by IRSF, as the demonstration was done with live-data, the variance between flight plan and actual arrival time during the demonstrations could not be seen as real result. This is based on that IRSF often lowered the arrival flight time, thereby making the variance between actual landing time and flight plan higher while lowering fuel burn, CO2 emissions and arrival flight time. The reason for the difference between the result in the V3 validation and the demonstration is that during the V3 validation IRSF was used with pre-defined scenarios and the ATCO interacted with the system thereby making all the system connected and the flight plan was thereby impacted by IRSF.

During the VLD demonstration IRSF only used live-data that was not processed by the operational controllers, making the variance bigger when lowering flight times as real flight operations could not be affected. It is important to notice that predictability and punctuality was observed to be improved by the system when observations on additional ghost flights (not live Flight Plans) and suggested times from the system was performed and compared.

C.3.3 Unexpected Behaviours/Results

During the demonstration the radar screen did crash during a few occasions, this could be solved by restart of the systems in demo setup. This did not affect the Enhanced DMAN or IRSF negatively, thereby not affecting the demonstration of important aspects negatively. The radar screen was used to visualise the flightpath of the aircrafts.

The amount of traffic at Stockholm-Arlanda was due to the effect of covid not with the normal high traffic levels to fully demonstrate that the solution could increase capacity (this have also been verified in PJ02-08 V3 real time simulation).

C.3.4 Confidence in the Demonstration Results

Level of significance/limitations of Demonstration Exercise Results

The VLD demonstration in Arlanda tower building used recorded live data, due to the technical setup set-up in an open conference room. This was known prior to start of demonstration and did thereby not affect the demonstration of important aspects.

Quality of Demonstration Exercise Results

The results from the demonstrations are based on questionnaires, debriefings, expert judgement and observation of system performance when using presentation of live traffic and also of recorded traffic. The data collection and analysis are seen to be of high quality based on data received through good questionnaires and observations of the system.

Significance of Demonstration Exercises Results

Observations has been performed on different flights on different days and information was gathered from persons with different work tasks and different views of the solution. Thereby has the risk for false results been minimized.

The SESAR large scale demonstration confirmed the ability to increase runway throughput by early and enhanced planning of an integrated runway sequence, applicable both in single runway operations, dependent runways and when using the two parallel runways in mixed mode.

According to the environmental permit for Stockholm-Arlanda Airport, up to five additional arrival flights per hour can land on the runway mainly used for departures (when runway configuration is set to use the parallel runways in segregated mode).

C.4 Conclusions

IRSF has, during the long demonstration periods, worked without any problems or crashes, this indicates that the system is stable and can handle live-data during longer periods of time. The demonstrations proved that the solution and the system still reach the earlier validated results from the V3 real time simulation. KPAs such as **capacity**, **efficiency**, **predictability** and **safety** has also been demonstrated with positive results, showing that there are benefits to be made for the airports that choose to use a system based on IRSF.

C.4.1 Increased runway throughput at Stockholm-Arlanda Airport

During the demonstration of IRSF, including dialogue with operational staff at Airport, ATC and organisations, two main options for increased capacity were identified;

C.4.1.1 Arlanda Airport – a plan for the future

New report “Arlanda Airport – a plan for the future” is provided by the Swedish Government.

Arlanda Airport - a plan for the future (2022-06-14/Ds 2022:11)

Note: translated parts

5.4 The capacity of taxiways, taxiways and stands must be able to meet demand over time.

Proposal: Swedavia should work to ensure that, even in the long term, there will be sufficient capacity at the airport in relation to the demand that exists.

Swedavia should therefore start with full force and take the necessary preparatory measures so that the capacity for take-offs and landings at Arlanda can be expanded when needed.

These efforts should include all types of measures, from for example the introduction of parallel mixed operations at current runways (both departures and arrivals), to building additional runway entry's/exit's, the introduction of congestion charges and the construction of a new parallel taxiway. All with the aim of strengthening capacity.

The preparatory measures should be carried out in such a way that a possible environmental assessment process can be started without further delay.

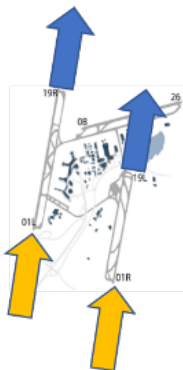
IRSF can with early planning of an integrated runway sequence, allocate aircraft for departure and landing when the parallel runways are used in mixed mode. Additional IRSF functionality will be to balance flights between the parallel runways to minimize delay and congestion, both in the air and on the ground.

The use of IRSF will also be an enabler to in an efficient manner predict and plan flights when operating the parallel runways in mixed mode (departures and arrivals on both runways), including balancing of flights between the runways to further improve efficiency and ensure high-capacity levels.

The introduction of IRSF will be a short-term option to support efficient planning for operational use of RNP-AR and overall advanced curved operations and approaches with capability to increase runway throughput with 5 arrivals per hour and minimizing the noise over noise sensitive areas.

Sustainable airport operations with IRSF to enable a long-term efficient use of mixed mode on both parallel runways to increase capacity; See Figure 39.

RWY 01L and 01R



Parallel runways in mixed mode

- Total of 90 movements
 - 45+ movements per runway
- Balancing between runways
- Efficient management of arrival peak and departure peak

RWY 19R and 19L



Figure 40: Parallel runways at Stockholm-Arlanda in mixed mode

C.4.1.2 Environmental permit for Stockholm-Arlanda Airport

New “Environmental permit for Stockholm-Arlanda Airport” allowing up to five additional arrivals to land on runway mainly used for departures (when the parallel runways are in use). IRSF can with early planning identify aircraft able to use an RNA-AR approach to land on the “departure runway”.

Environmental permit for Stockholm-Arlanda Airport (2021-10-15/M 6547-20)

Note: translated parts

B. Permission to use alternate approach procedures based on Established on RNP (EoR) as follow;

- *Approaches to runway 01R (straight or curved) and runway 01L (curved) in combination with departures from runway 01L.*
- *Approaches to runway 19L (straight) and runway 19R (curved) in combination with departures from runway 19R.*

The permit applies to a maximum of five approaches according to the respective point during one hour.

Sustainable airport operations with IRSF to enable short-term efficient support for an increased number of RNP-AR STAR's. See Figure 40. This will have a positive impact, with reduced emissions and also reduced noise levels over noise sensitive areas.

Approach to RWY 01L short RNP-AR STAR allocated before TOD

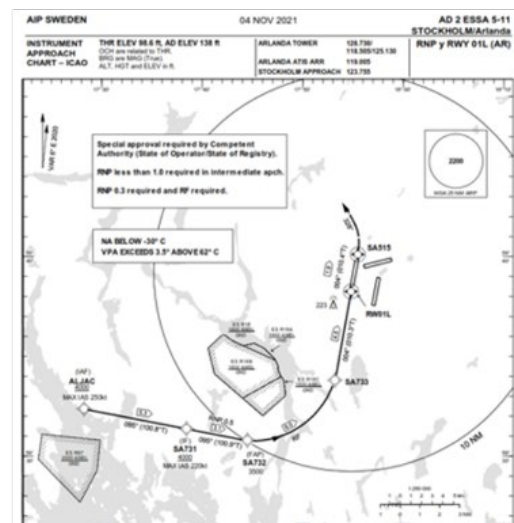


Figure 41: Short curved RNP-AR STAR to runway 01L

C.4.1.3 Allocation of RNP-AR STARs before top of descend

With the use of IRSF an improved shared situational awareness between TWR and APP and also with ACC has been identified and confirmed.

It is recommended to ensure presentation of IRSF AMAN information for upstream En-route ATCOs, also to adjacent ACC/FIR. In this way an RNP-AR STAR can be allocated and provided by ATC to the flight crew before top of descend.

C.4.1.4 New runway entry's for runway 01L and runway 19R

Implementation of new additional intersection for departures to entry the runway, provide increased flexibility to meet the planned sequence in mixed mode operations. The option with new intersections as very valuable to increase flexibility in which aircraft to depart first, to ensure high runway throughput. The negative effect of aircraft number one with delay, blocking the runway entry will be minimised.

C.4.1.5 Enhanced winter operations with predictable de-icing

During the VLD demonstrations tower controllers/supervisors, airport operators and ground handling, all expressed the importance in the use of IRSF to also include efficient planning and execution of de-icing at the airport. By including planned de-icing start/end times to be included into the integrated planning of runway sequence, the quality of departure target off block times and target take-off times can be met during the winter period. For Stockholm-Arlanda there is a long period for de-icing of departure flights, mainly from November to March.

With IRSF linked to Airport CDM and a developed interface to the companies providing de-icing the airport winter operations can be predictable and enhanced, both during normal and adverse conditions.

C.4.1.6 Presentation of airport ground radar for the approach sectors

One internationally recognised way to improve awareness and operational efficiency is to provide presentation of the airport ground radar for the approach controllers. This will reduce the need of coordination between tower and approach and also increased the situational awareness for approach.

C.5 Recommendations

C.5.1 Recommendations for industrialization and deployment

Knowledge from V3 validations and VLD can be used as requirements for further development in order to industrialize and deploy the solution. There is a need to do an in-depth study regarding what operative system might be affected, changed or needed to be installed or removed in order for the solution to work. An in-depth study regarding time required for the different steps of the industrialization and deployment are also needed in order to have a complete deployment roadmap. The recommended way to deploy the system, according to operative experts, are stepwise which will allow for minor problems to be identified and solved along the deployment phase without interfering with operative systems.

There need to be a dialogue and close coordination with an industry partner during the industrialization and deployment phase to conduct the in-depth studies as well as working with system to meet both operational and system requirements.

The new study "Arlanda Airport – a plan for the future"; address the introduction of parallel mixed operations at current runways (both departures and arrivals), including start of the linked environmental assessment process.

The present “Environmental permit for Stockholm-Arlanda Airport” allowing up to five additional arrivals to land on runway mainly used for departures (when the parallel runways are in use). The use of IRSF will enable short-term efficient support for an increased number of RNP-AR STAR’s and provide sustainable airport operations.

The use of Integrated Runway Sequence Function will be an enabler to increase runway throughput and provide high flexibility to reduce emissions.

- a) The use of IRSF can support an efficient management of up to 90 movements per hour at Stockholm-Arlanda by a predictable use of the parallel runways in mixed mode operations.
- b) When using the parallel runways in mixed mode additional runway entry’s for departures at runway 01L and 19R will enhance flexibility to ensure high runway throughput.
- c) By early setting of runway sequence, allocation of RNP-AR approaches can be set before arrival flight top of descend and increase flight efficiency when an optimal flight profile can be used. This will also support an increased use of short curved approaches to minimise noise over sensitive areas.
- d) The use of IRSF provide an improved shared situational awareness between TWR, APP and also with ACC. It is recommended to ensure presentation of IRSF AMAN information for upstream En-route ATCOs, also to adjacent ACC/FIR. In this way an RNP-AR STAR can be allocated and provided by ATC to the flight crew before top of descend.
- e) In the VLD demonstration ATCOs confirmed the need for presentation of an airport ground radar display at the approach sectors, to improve situational awareness and operational efficiency.
- f) Predictable de-icing for enhanced winter operations. With IRSF linked to Airport CDM and a developed interface to the companies providing de-icing the airport winter operations can be predictable and enhanced, both during normal and adverse conditions.
- g) Trajectory prediction with a high quality and integration of A-SMGCS data (including target-time to threshold) will enhance the quality of IRSF predictions.

Implementation of IRSF is in line with and supporting a number of other initiatives;

- New airspace design
- Curved approaches
- Time based separation in approach

There are options for a stepwise implementation of IRSF at Stockholm-Arlanda;

- DMAN functionality with display of arrivals
- Display departures in AMAN
- Fully Integrated Runway Sequence in both DMAN and AMAN

C.5.2 Recommendations on regulation and standardisation initiatives

The processes for handling a new system based on IRSF will be the same as the airport CDM procedures already in use. No further change to regulations and standardisation is seen as required.

Appendix D WP4 - PWS and iROT- Optimised ROT spacing principles and regulatory framework

D.1 Abstract

The present Appendix D to the Demonstration Report (DEMOR) describes the analysis principles of an arrival traffic dataset from a major European airport, and the application of the PJ02.08.03 'ROCAT/iROT' solution logic of optimised spacing based on local characterisation of Runway Occupancy Time (ROT).

The Runway Occupancy CATegorisation, i.e. 'ROCAT', solution for Arrivals, developed under the SESAR2020 programme as PJ02.08.03, defines a methodology to establish a local categorisation scheme with optimised arrival distance minima due to ROT factor, supporting increased runway throughput.

The analysis is based on a representative dataset of arrival traffic surveillance data with associated meteorological conditions, covering at least a 1-year period. According to the ROCAT/iROT solution principles, the arrival ROT analysis is primarily made per runway direction (i.e. magnetic heading or QFU) and aircraft types, with the derivation of corresponding local individual ROT spacing minima, applicable to the airport environment as use case.

For the evaluation of corresponding benefits on Runway Throughput, the global assessment combines the effect of several optimization of separation standards related to wake turbulence separation, surveillance separation and ROT spacing for arrival separation management. It assesses the separated and combined effect of static pairwise wake turbulence separation (as per PJ02.01.04), minimum surveillance/Radar separation down to 2.0 NM (as per PJ02-03 solution) and individual Runway Occupancy Time (iROT) spacings.

This appendix report also presents the needs and initiation of standardisation and regulatory evolution which will support and enable the future deployment. Since ROCAT/iROT is originally based on ICAO provisions, EUROCONTROL has engaged with ICAO about possible evolution of the regulatory provisions, has proposed amendment and initiated regulatory evolution process in support of deployment

D.2 Optimised ROT spacing: ROCAT/'iROT'

Based on the locally defined ROT, the first step in ROT spacing optimization is the characterization of the ROT for each flight. The analysis shall cover at least a full year (4 seasons) of representative operations and all runways for which ROT spacings are intended to be optimized. The analysis shall be performed based on data provided by the local airport. From this dataset, a characterization of the ROT shall be performed at least, per landing runway and per aircraft type. Note that the characterization shall be performed for peak operations, during which aircraft tend to vacate the runway earlier due to higher traffic pressure.

One of the two methods identifies in the PJ02.08.03 ROCAT solution is based on the average AROT (Arrival Runway Occupancy Time) and the conversion into a corresponding distance using a reference conservative aircraft speed (the other method is based on the ROT distribution and is not here developed and applied further).

The conversion of individual time-based ROT into distance-based ROT spacing relies on the link, established in ICAO PANS-ATM doc 4444, between reduced MRS and ROT. In that document, it is stated that MRS= 2.5 NM can be safely applied provided that the average ROT does not exceed 50 s. It thus establishes a direct link between average ROT and associated distance spacing. In order to convert a time separation of 50 s into a distance separation of 2.5 NM, a (ground)speed of 180 kts is used as $50 [s] \times 180 [kts] / 3600 = 2.5 [NM]$.

This reference speed of 180 kts is obviously conservative as no aircraft travelled the last 2.5 NM down to landing threshold at such a high speed during peak operations. It therefore introduces a buffer in the distance-spacing calculation accounting for uncertainty on:

- Leader ROT that can be larger than the average, and
- Follower flight speed that varies from one flight to another.

The here-proposed methodology extends this logic on two aspects:

1. Rather than considering the average ROT of the whole traffic, the average ROT is computed for subsets of the traffic;
2. Rather than setting a ROT threshold to apply 3 or 2.5 NM spacing, the individual ROT spacing is computed directly from the individual average ROT and the reference 180 kts groundspeed:

$\text{iROT distance behind type Z on RWY XX [NM]} = \text{average ROT}_{\text{type Z, RWY XX}} [s] \times 180 \text{ kts} / 3600$
--

For example, on runway XX

- 2.6 NM of ROT spacing can be applied behind aircraft type Z if its average ROT is 52s
- 2.8 NM ROT spacing can be applied behind aircraft type Y since if average ROT is 56s.

The final results of individual ROT spacing ('iROT') is thus a table providing per runway and per aircraft type (and possibly per airlines), the applicable ROT distance spacing applicable behind that flight.

Note that for rarer aircraft types or less frequently used runway(s), the ROT might not be characterized with sufficient statistical relevance. For those cases, the ROT spacings shall correspond to the surveillance separation or any other larger ROT-based spacing currently applied locally. The iROT spacing minima can then possibly be grouped between aircraft type categories of ROT, defining a local 'ROCAT' scheme.

D.3 Database description and processing

To assess the combined deployment of the wake, surveillance and ROT separation/spacing optimization, an operational database was made available. This database covers at least 1 year of surveillance and MET data covering all arrivals.

The surveillance data contain time-stamped latitude/longitude coordinates and altitudes for the various flights with the corresponding flight information (aircraft type, airline, etc.). The MET data contains surface anemometer wind data and METAR information. Those MET information were not used for the present study.

Based on the surveillance data, for each track, each track is processed following various steps:

- the landing runway is first detected;
- the time at landing runway threshold is then computed through interpolation in the track;
- the runway exit is then detected;
- finally, the time at runway exit is calculated through interpolation;
- Time separation with follower aircraft based on detected times at landing threshold.

Note that the time at runway exit is here defined as the time at which the surveillance data point is on the runway edge toward the runway exit. The AROT is then computed as the difference between the time at runway exit and the time at runway threshold.

Note also that the Reduced Runway Separation Minima (RRSM) (i.e., considering the runway as vacated when the flight passed a point located at 2400 m from the runway landing threshold) has not been considered in the present exercise.

Two filtering steps are then applied:

- Exclusion of the cases for which the landing detection or the runway vacation detection was not possible due to noisy or missing surveillance data;
- Exclusion of cases for which the time separation with the following traffic is smaller than the measured ROT, indicating a problem with either the landing or the runway vacation detection.

Finally, for ROT characterization, only flights operating in 'constrained' conditions are retained. We here define a flight as constrained if it is followed by another flight landing on the same runway in at least the next 4 minutes.

For example (notional), the fraction of operation on each landing runway is provided in Table 26.

'RWY #1'	'RWY #2'	'RWY #3'
73%	18%	9%

Table 26: Example Fraction of landing operations on each runway

D.4 iROT minima determination for an Airport

Based on the database described in Section D.3, for each main landing runway and for each aircraft type sufficiently frequent in the operational dataset (i.e., at least 50 tracks in peak operations), the average runway occupancy time is computed.

These average ROT are then converted into iROT spacing distances using a reference speed of 180 kts, according to the iROT methodology recalled in Section D.2. Note that the obtained iROT spacing are not capped up to any value. Hence, some values above 3NM are obtained for aircraft types and runway combinations with average ROT above 60 s.

D.4.1 Runway effect and iROT minima

The various average ROT are compared from one runway to another, see **Table 27**. Because of the exit locations, as expected, the AROT are seen to be larger for Medium aircraft types when operating on Runway #1 compared to Runway #2 or 3. Note however that for Heavy aircraft types, the difference in AROT between Runway #1 and 28 is more limited. AROT on Runway #1 are even smaller compared to those on Runway #3.

ac type	RWY #1	RWY #2	RWY #3
A388	64.6	87.7	73.0
A332	61.6	60.7	69.5
A333	60.9	53.7	65.8
A343	61.2	55.2	68.6
B763	59.8	60.3	65.5
B77W	64.1	62.8	71.4
A318	63.3	49.0	52.2
A319	58.1	47.2	49.3
A320	56.2	47.2	48.4
A321	54.6	47.5	48.5
B737	57.5	53.6	53.9
B738	55.5	57.0	58.2
BCS1	57.9	47.9	46.9
BCS3	56.0	47.1	46.4
C56X	59.5	46.3	50.3
CL60	61.3	47.0	48.6

ac type	RWY #1	RWY #2	RWY #3
CRJ9	54.4	46.1	49.5
DH8D	54.5	47.4	51.0
E170	56.1	47.0	52.5
E190	55.0	44.7	44.2
F100	54.3	44.1	44.3
FA7X	60.4	50.1	53.0
GLEX	61.1	51.4	57.6
GLF5	65.3	54.0	59.5
RJ1H	57.6	45.5	45.0
SB20	54.2	43.6	43.9

Table 27: Average ROT observed for the types found on the various runways [s]

For completeness, **Table 28** provides the corresponding iROT minima obtained for the various types on the three runways.

ac type	RWY #1	RWY #2	RWY #3
A388	3.2	4.4	3.6
A332	3.1	3.0	3.5
A333	3.0	2.7	3.3
A343	3.1	2.8	3.4
B763	3.2	3.1	3.6
B77W	3.0	3.0	3.3
A318	3.2	2.4	2.6
A319	2.9	2.4	2.5
A320	2.8	2.4	2.4
A321	2.7	2.4	2.4
B737	2.9	2.7	2.7
B738	2.8	2.8	2.9

ac type	RWY #1	RWY #2	RWY #3
BCS1	2.9	2.4	2.3
BCS3	2.8	2.4	2.3
C56X	3.0	2.3	2.5
CL60	3.1	2.4	2.4
CRJ9	2.7	2.3	2.5
DH8D	2.7	2.4	2.6
E170	2.8	2.4	2.6
E190	2.8	2.2	2.2
F100	2.7	2.2	2.2
FA7X	3.0	2.5	2.6
GLEX	3.1	2.6	2.9
GLF5	3.3	2.7	3.0
RJ1H	2.9	2.3	2.3
SB20	2.7	2.2	2.2

Table 28: iROT minima for the types found on the various runways [NM]

D.4.2 Yearly effect

For each landing runway, the sensitivity of the iROT minima to the period of measurement can be performed by comparing the average ROT and the corresponding iROT minima when using each year of measurement separately or when combining the 'x' years of measurements.

D.4.3 Runway exit distribution

For each landing runway, the runway exit usage for each type can be assessed.

D.4.4 Operator effect

For each landing runway, the sensitivity of ROT to the operator is performed by comparing the runway exit usage and the average ROT for the home-based carrier flights, with pilot more familiar to the airport layout/ runway exit configuration, to the same types operated by other operators on the same landing runway

D.4.5 Local ROCAT scheme

In order to facilitate the application without separation/spacing delivery tool/indicator, it is then possible to create ROT spacing CATegories, by regrouping aircraft types on the basis of their iROT

spacing values, and rounding to achieve a 0.5NM or 1NM increment (e.g. 2.5NM for some or 3NM for others).

D.5 Benefits related to iROT spacing and wake separation scheme

In order to assess the benefits related to the various solutions, we here calculated the average (i.e., weighted by the observed traffic mix on each runway) separation/spacing minima. To do so, for each pair, we compute:

- The minima guaranteeing fulfilling applicable wake, surveillance and ROT minima
- The probability to observe that pair on that runway (assumed to be equal to the product of the probability to observe each of the aircraft types)
- The probability to operate on that runway

The average minimum per runway is then obtained as the sum of the product applicable minimum times pair probability on this runway.

The global average on all airport operations is obtained as the sum of the average separation minima per runway times the probability to operate on that runway.

The average separations are obtained from pairwise separation matrices obtained when applying the investigated wake turbulence scheme (ICAO WTC, RECAT-EU or RECAT-PWS) with the investigated ROT spacing (iROT or 3NM) and the investigated MRS (3, 2.5 or 2 NM).

The obtained separation matrices were provided. Likewise, the average separation minima were provided and compared in a separate document.

The obtained landing throughput is directly linked to the applied time separations between the aircraft. For given traffic mix, in given wind conditions, assuming no change in speed behaviour, those time separations are directly related to the applicable distance-based minima and the buffer taken by the controller in their delivery.

The benefits related to the various solutions is thus here assessed assuming:

- An average separation delivery accuracy of 0.5 NM compared to the minima (i.e., typical value for peak arrival traffic)
- No change in speed behaviour nor separation delivery accuracy when reducing the applicable minima.

The benefits are then obtained as :

$$(\text{Avg sep}_{\text{baseline}} - \text{Avg sep}_{\text{solution}}) / (\text{Avg sep}_{\text{baseline}} + 0.5 \text{ NM}).$$

Here, the considered baseline is ICAO with 3NM MRS/ROT spacing.

It must be noted that the benefits are assuming that no other larger spacing constraint are applicable (e.g. in TMA) and we can therefore take full advantage of the reduced arrival ROT spacing minima.

D.6 Standardization and Regulatory evolution

This section complementary addresses the needs and possible evolution of standards/guidelines, as well as regulatory provisions at European or global level.

D.6.1 Operational solutions and REG/STD needs

D.6.1.1 ROCAT and reduced spacing overview

The 'ROCAT' solution for Arrivals, developed under the SESAR2020 programme as PJ02.08.03, defines a methodology to establish a local scheme with optimised arrival distance minima due to ROT factor, supporting increased runway throughput.

The minima are derived on the basis of analysis of local AROT observations characterized at least per runway and per aircraft type. The conversion of these times into distance spacing minima relies on ICAO PANS ATM doc 4444 principles already applicable for reduced 2.5NM spacing.

Runway occupancy time is typically defined as the time between the aircraft passing over the landing runway threshold and the time taken to vacate the runway. This occupancy time is influenced by a variety of factors, which include the runway configuration, exit location, individual aircraft type characteristics, performance and configuration for landing, deceleration and pilot strategy for selecting runway exit and vacation, as well as flight conditions. Therefore, runway and aircraft type are the two main influencing features.

For a large number of aerodromes and Approach ATS units, and on specific runways, there is usually a part of the traffic/aircraft types for which the average ROT is lower than 50 seconds. This is typically Medium wake category aircraft types, either the case of large single-aisle (e.g. Airbus 320/Boeing 737) models or the case of Regional jets, depending on the specific runway configuration, and these aircraft 'groups' can represent more than 50% of the local arriving traffic. These aerodromes could benefit significantly if those aircraft and corresponding flights were able to apply the 2.5NM separation and benefit from the 0.5 NM reduction when all criteria, including the ROT, are met. Based on a unique characterization of each specific runway, an individual/'pair-wise' (based on the lead traffic behaviour) Runway Occupancy Time ('iROT' /'ROCAT-PWS') per aircraft type can be assigned and with this information ATC could define two aircraft sub-categories based on ROT. For example, the Medium category could be subdivided in two: one with average ROT lower than 50s for which the 2.5 NM reduced surveillance minima can be applied, and one with average ROT of greater than 50s for which the 3 NM spacing remains necessary. Under SESAR 2020 PJ02.08.03 validated solution, this concept is referred to as 'ROCAT' (Runway Occupancy CATegories) and/or ROCAT-PWS spacing.

There are several ways to operate the ROCAT for selected aircraft type pairs in view of upgrading the applied ROT-spacing: on a categorical system basis – 'ROCAT' (on a procedural basis or with automation support / ATC separation delivery tool such as for TBS-ORD solution) for quick wins, or on an individual leader aircraft type/pair-wise basis – 'ROCAT-PWS' (with necessary ATC separation delivery tool), for maximising the arrival throughput benefits

D.6.2.2 Relevant Regulatory references

On this basis, given the evolved applicable separation minima (TBS, S-PWS, MRS) and spacing (ROT) principles, the following ATM regulatory reference are identified as being subject to evolution,

- **EASA 2017/373 Part-ATS**
- **ICAO Doc 4444 PANS-ATM**

In particular, the chapter 8.7.3 on separation minima (surveillance and wake turbulence minima)

Doc 4444 8.7.3 establishes the provisions for separation minima based on ATS surveillance systems:

- *8.7.3.1 Unless otherwise prescribed in accordance with 8.7.3.2, 8.7.3.3 or 8.7.3.4, or Chapter 6 (with respect to independent and dependent parallel approaches), the horizontal separation minimum based on radar and/or ADS-B and/or MLAT systems shall be 9.3 km (5.0 NM).*
- *8.7.3.2 The separation minimum in 8.7.3.1 may, if so prescribed by the appropriate ATS authority, be reduced, but not below:*
 - *a) 5.6 km (3.0 NM) when radar and/or ADS-B and/or MLAT systems' capabilities at a given location so permit; and*
 - *b) 4.6 km (2.5 NM) between succeeding aircraft which are established on the same final approach track within 18.5 km (10 NM) of the runway threshold.*
- *(...)*

8.7.3.2 b) permits the application of 4.6 km (2.5 NM) provided several conditions are met. The first listed criterion states that the average runway occupancy time of landing aircraft is proven, by means such as data collection and statistical analysis and methods based on a theoretical model, not to exceed 50 seconds.

Other conditions for operating reduced surveillance minima address the surveillance performance and the assurance that the aircraft can safely and efficiently vacate the runway.

It is typically understood and appears implicit in the PANS ATM provisions that, if the average runway occupancy time (ROT) criterion is not globally satisfied, the reduced 2.5 NM separation minima cannot be applied. This is regardless of the fact that a large part of the traffic might meet this ROT criterion and that all the other criteria from 8.7.3 are met (e.g., suitable surveillance performance).

Given that ROCAT provides an alternative (more efficient) spacing constraint, relying on existing ICAO / EASA requirement (linked to the criteria for operating reduced separation on final approach down to 2.5NM), there is an interest in evolving these to encompass the possibility of more individualised application and facilitate local/national regulatory acceptance, as well as developing guidance material for facilitating understanding of this more complex separation scheme.

D.6.2 REG evolution

Based on the operational / regulatory impact, and related references, the following regulatory evolution needs are identified, with the corresponding international regulatory bodies

D.6.2.1 EASA 2017/373 Part-ATS

- Development of corresponding AMC / Proposal for Amendment (PfA) into the Part-ATS of regulation EC. 2017/373 Common requirements for Air Traffic Management / Air Navigation Service with ROCAT (based on ICAO PfA, since ICAO developments are expected to take place first)

D.6.2.2 ICAO Doc 4444 PANS-ATM

- Proposal for Amendment of the ICAO Document 4444 PANS-ATM on ROCAT

It is important to note that the ROCAT solution fully relies on existing provisions, and is only based on a differentiated application of ROT criteria for operating the reduced surveillance minima, based on local characterization specific to a given runway and per pair of individual arriving aircraft types.

D.6.3 Engagement with REG bodies and initiation of REG evolution

D.6.3.1 ICAO

In coordination with the ICAO Air Navigation Bureau Secretariat, EUROCONTROL has proposed to develop a Proposal for Amendment (PfA) of Document 4444 PANS-ATM with provisions enabling optimised ROT spacing based on categories (ROCAT) or individualised (iROT) on final approach.

ICAO SASP (Separation and Safety Panel)

An information paper and related presentation was delivered at SASP WG/36 in May 2022, following by a working paper and related presentation delivered at SASP WG/37 in November 2022, resulting in an agreement to create a job card for developing a proposal for amendment.

D.6.4 STD / GUID support

D.6.4.1 EUROCONTROL Guidelines

In order to support the implementation and facilitate the understanding of the SESAR Solution PJ02.08.03 and related V3 data pack, EUROCONTROL is developing a EUROCONTROL Guidelines document capturing the requirements and knowledge gained during the SESAR V3 validation exercises conducted with various airport environments.

D.6.5 Next steps

The following next step are expected for progressing the regulatory framework evolution:

- Amendment of PANS-ATM with ROCAT, followed by EASA AMC
- Publication of EUROCONTROL guidelines on ROCAT

Appendix E WP2/WP4 – ML/AI workshop and results on PWS, ROT and Time to Fly

E.1 Preface

In WP2/WP4 a few dedicated workshops were held. One of those explored and discussed the advances on Machine Learning (ML) technics and Artificial Intelligence (AI) logic for application in PWS/ROT/MRS separations as well as for potential inclusion in the WP2/WP4 exercise context. NATS had also worked internally on ML/AI, as well as EUROCONTROL (in the PJ.02-W2 project), see also Appendix D on ROCAT/IROT. Experiences between for these partners for ML/AI application of ROT spacing predictions for Heathrow, Schiphol and Zurich Airport were exchanged.

The current Appendix E provides the WP2/WP4-related ML/AI ROT support work performed by NLR for Schiphol Airport and some main results. Some results however remain confidential for the time being. The workshop, study outcome and overall impression was that ML/AI prediction models certainly have a potential for future application by ATC, for instance in the context of ROT and T2F (hence spacing separation) prediction aspects, but still require more accurate prediction models. Partly this should be achieved via better quality data, more additional data (and data sources), and particular feature inclusion to improve the ML/AI models; expected runway exits, aircraft mass and autobrake setting of an aircraft, (e.g. brake-to-vacate inputs of Airbus downlinked), specific airline behaviour, and more operational inputs, like ATCo behaviour models and/or pilot models. This all needs to be further (better) understood before ML/AI can be introduced operationally. Hence the inclusion of ML/AI prediction models in the WP2/WP4 exercise was no longer foreseen.

E.2 Summary of the ML/AI work

This Appendix E describes the setup and first results obtained for predictive modelling of the time to fly (T2F) to the runway threshold and runway occupancy times (ROT) during the final approach at Amsterdam Airport Schiphol using random forest machine learning algorithms. Incorporating accurate predictions of the time to fly and runway occupancy times in air traffic controller support tools or the air traffic control system could potentially enable controllers to handle traffic more efficiently and safely.

Modelling was done using a dataset containing around one million flights ranging from 1st of January 2016 to 29th of February 2020. The models in this study were trained to make predictions of the time to fly and runway occupancy time at the 4 nautical mile to threshold point of the final approach. For the time to fly two scenarios were studied, in one of which features from the 5 nautical mile to threshold point were included in the feature set. For the runway occupancy time, models were developed for the case that the exit runway is unknown and the case that the runway exit to use is pre-determined.

For the time to fly prediction using random forests the best models were found to achieve a mean squared error of 15.7 s², regardless of whether features from the 5 nautical mile point were included in the data. This was found to be a considerable improvement over a baseline, where the mean time to fly was taken per runway and aircraft type, which resulted in a mean squared error of 55.3 s². Permutation feature importance calculations showed that the groundspeed of the aircraft at the 4 nautical mile point was the most important feature when predicting the time to fly.

In the case the runway exit was not included in the features of the runway occupancy time prediction models, the best model was found to achieve a mean squared error of 93.2 s². Thereby improving over

a baseline of 111.9 s² where the mean runway occupancy time per runway and aircraft type was taken as the predicted value. Model performance significantly improved when the runway exit was included in the features. The best random forest model achieved a mean squared error of 28.1 s², over a baseline performance of 47.4 s² where the mean rot per runway exit was taken as the predicted value. It was found that the runway exit to be used was the most important feature when predicting the runway occupancy time, followed by the RECAT-EU wake vortex category of the aircraft.

For the time to fly prediction the random forest models achieved a significant improvement over the baseline. For the runway occupancy time prediction models the improvement over the baseline was limited, and using the runway occupancy time predictions in practice would arguably require an improvement in performance. It was shown that the runway exit used was the most important feature for accurate runway occupancy time predictions. A possible way forward would be to train a classifier model to predict what exit is most likely to be used and to add this as a feature to the regression model.

A number of features that were found to be important in previous studies were not included in the dataset that was currently used. Two of those features were the airline operator and the separation to the succeeding aircraft. Adding these features could potentially offer an improvement in the prediction performance.

Incorporating time to fly and runway occupancy time predictions in the air traffic control operations would require a thorough understanding of the current procedures and extensive cooperation with the intended users of the tools. Therefore it would be useful to think about how time to fly and runway occupancy time predictions can be used in the air traffic control system in practice and how they be can integrated in support tools for the air traffic controllers.

E.3 Introduction to the ML/AI work

While the global aviation sector is still experiencing a major reduction in transportation numbers caused by the Covid-19 pandemic, the sector is planning towards recovery. Innovative solutions and changes to the concept of operations are being made and implemented with the goal of achieving safer and more efficient operations. For an ANSP (Air Navigation Service Provider), a high throughput of traffic is essential for facilitating more movements within the airspace. Especially throughput during approach and landing is a key factor when determining the peak capacity of an airport and its TMA (Terminal Manoeuvring Area).

An important factor that limits the throughput of an airport is the spacing that is required between two aircraft (i.e. an aircraft pair) on final approach. Dependent on the surveillance system of the ANSP (air navigation service provider) on that airport and the wake turbulence categories of the aircraft pair, a specific separation minima must be applied between two aircraft. This separation minima, which is often expressed in distance (i.e. DBS (Distance Based Separation)) usually consists of two types of separations, namely radar separation and wake turbulence separation.

By reducing separation minima, a higher throughput on final can be achieved. Separation minima can be reduced by implementing a different wake vortex categorization scheme, such as RECAT-EU [E.1] or RECAT-EU-PWS (PairWise Separation) [E.2], compared to the currently widespread in operation ICAO Wake Turbulence Categories [E.3]. Whilst reducing separations towards RECAT-EU is considered an acceptable safe solution, with the introduction of smaller separation minima, operations become more constraint and safety margins become smaller. Accurate predictions of the TTF (Time-To-Fly) and ROT (Runway Occupancy Time) have the potential to assist ATCO's (Air Traffic Controllers) with

decision-making on final, such as issuing speed reductions, clearance to land or instructing a missed approach when a (possible) under separation seems likely to occur.

This Appendix describes an introduction into modelling the TTF and ROT at AAS (Amsterdam Airport Schiphol) by means of machine learning methods. The project makes use of aggregated track data that was provided by ATC The Netherlands, hereafter named LVNL (Luchtverkeersleiding Nederland). Subsequently, this data was processed, integrated with additional datasets and used to train Random Forest regression models which predict the TTF and ROT for a given aircraft for different scenarios.

The structure of this Appendix E is as follows. Chapter E1 provides the preface, Chapter 2 the summary. Chapter 3 some background and literature information Chapter E.4 describes the operational framework of TTF and ROT predictions. Chapter E.5 describes the methodology of this machine learning study, including the dataset that was used. Chapter E.6 describes main results of the modelling phase, including the feature importance and the performance of the models. In Chapter E.5 the conclusions and recommendations are described.

E.4 Previous Work/Literature

This section describes the previous work and some literature that was found and analysed on the topic of predicting TTF and ROT prediction.

E.4.1 Landing operations

The final approach is the last leg in an aircraft's approach to a runway, from Final Approach Fix (FAF) to runway touchdown point. See Figure 41. During this leg the aircraft is established on the glideslope (GS) flying straight-in towards the touchdown point on the runway. After touchdown the aircraft rolls out and exits the runway. The air traffic controller directs the pilot towards the final approach segment taking into account other approaching and departing traffic. Once on the final approach the controller has limited control over the aircraft but assures the safety of the landing runway by providing a timely landing clearance. Only for safety infringement purposes the controller can request a go-around removing the aircraft from the active approach sequence. For a controller to safely separate traffic the controller applies the applicable separation standards taking into account the expected separation development. As a result of the so-called 'compression effect' aircraft will creep up to each other due to differences in speed.

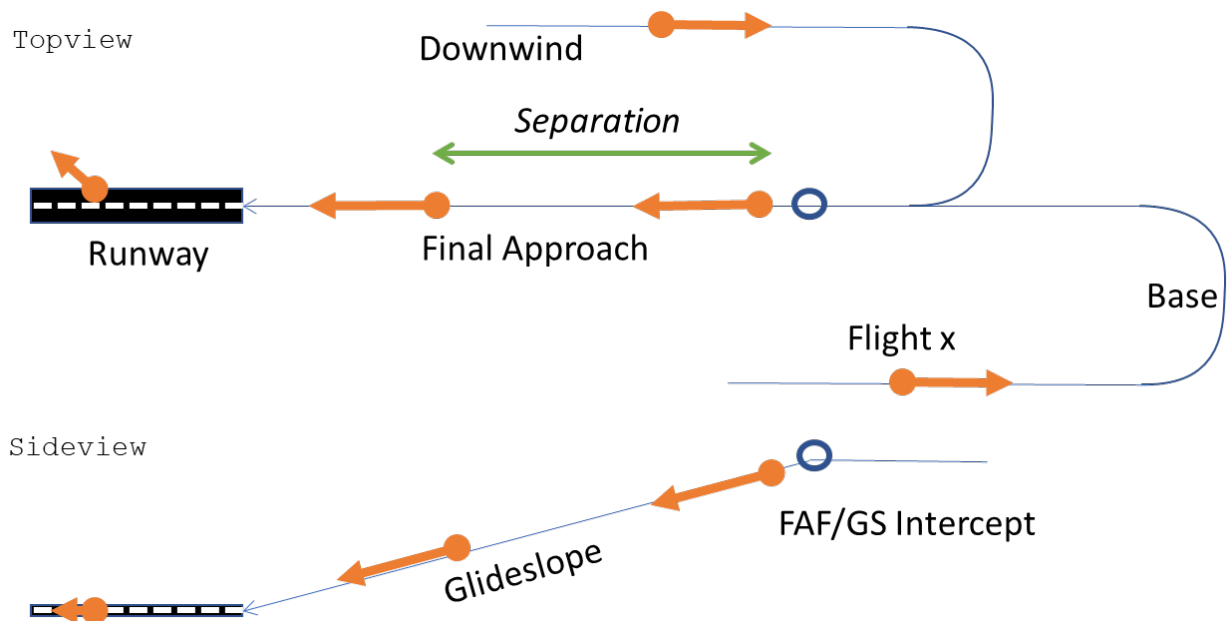


Figure 42: Separation between subsequent flights on final approach to the runway (top view + side view).

To ensure safe separation, and still have an optimal throughput a controller needs to:

1. predict the speed profiles of aircraft on final approach, and the runway occupation time,
2. predict the separation evolution for the converging traffic,
3. determine the separation minima applicable to successive aircraft, and
4. control the separation evolution to stay within the separation minima.

The speed profile of aircraft on final approach and during the landing roll depends on the aircraft performance characteristics, the environmental and runway conditions, and the airline operational policies. This is explained in more detail in the sections E.4.1.1 respectively E.4.1.2 on speed profiles.

The separation evolution depends on the starting conditions for the successive aircraft, the speed profiles of the aircraft, and the time to exit the runway. This is explained in the section on separation evolution.

The minimum separation during landing consists of three factors: the minimum radar separation, the applicable wake vortex separation, and the minimum required separation upon exiting the runway. This is explained in more detail in the section E.4.1.3 on separation evolution and section E.4.1.4 on separation minima.

If the separation of two successive aircraft is predicted to be below the minima it is up to the controller to resolve the situation. This is explained in more detail in the section E.4.1.5 on control.

E.4.1.1 Speed profile on final approach

The speed profile of an aircraft on final approach depends on the aircraft performance characteristics, environmental conditions and the operational procedures.

E.4.1.1.1 Aircraft performance characteristics

The aircraft performance characteristics influences the speed profile on final approach. Depending on the engine thrust, the aerodynamic drag and the aircraft weight the aircraft maintains horizontal speed or decelerates.

For each aircraft type the engine thrust is influenced by the thrust settings, atmospheric conditions and airspeed. The aerodynamic drag is influenced by the angle-of-attack, the flap and spoiler settings, gear selection, atmospheric conditions and airspeed. Together the thrust and drag determine in combination with the aircraft weight how the deceleration of the aircraft develops during final approach and landing.

The choices regarding the thrust setting and aerodynamic configuration is generally determined by the airline operational procedures belonging to the aircraft.

E.4.1.1.2 Environmental and runway conditions

Environmental conditions can be split into fixed and dynamic elements. The fixed elements are in principle the same during day-to-day operations and (quasi-) static. These include items like the runway exit positions. The dynamic elements change over time and include items like wind conditions.

- Static
 - Airport. In practice an increased airport height will result in an increase in the approach altitude. The true airspeed (TAS) increases with altitude.
 - Runway. Specific runways have influence on the aircraft performance by having a specific heading, length and location of the runway exits. The runway heading influences how the wind affects the aircraft ground speed. The runway length and locations of preferred exits influence flight crew choices regarding the preferred final approach speed. Furthermore, each runway has standard glideslope interception altitudes depending on the direction of arrival.
- Dynamic
 - Wind conditions influence the ground speed of the aircraft on final approach.
 - Weather conditions influence the expected braking action on the runway. This influences the choices of the flight crew regarding the preferred final approach speed, the needed rollout length and preferred runway exit. Furthermore, the actual temperature and air pressure influences the performance of the aircraft.
 - Runway condition: the runway surface conditions, e.g. dry, wet, ice or snow on the runway will influence the braking action. As a result pilots may choose to land with an adjusted Final Approach Speed (FAS).

E.4.1.1.3 Operational procedures

During the final approach the aircraft reduces speed in steps to the Final Approach Speed (FAS). During each step the flaps, gear and spoilers are set according to an operational schedule. In Figure 42 a typical approach speed profile is shown. The schedule is aircraft type and airline dependent.

The FAS, denoted as V_{APP} in the figure, is specific to each aircraft type, but is also influenced by the environmental and runway conditions. The flight crew will set the final approach speed accordingly. The actual conditions influencing the final approach speed are:

- The landing weight. A higher aircraft weight typically means the need for a higher FAS.
- The wind conditions. The expected average and gust wind conditions influence the FAS calculation. For tailwind no wind correction is applied. This wind correction differs per aircraft type.
- The flap configuration. When an aircraft has several flap configurations certified for landing a flight crew can make a choice regarding the flap configuration. Less than full flaps means the need for a higher FAS.
- The icing conditions. The expected runway braking conditions influence the choice regarding the FAS.
- Use of automation (like Auto throttle or Autoland) influences the choice regarding the FAS.

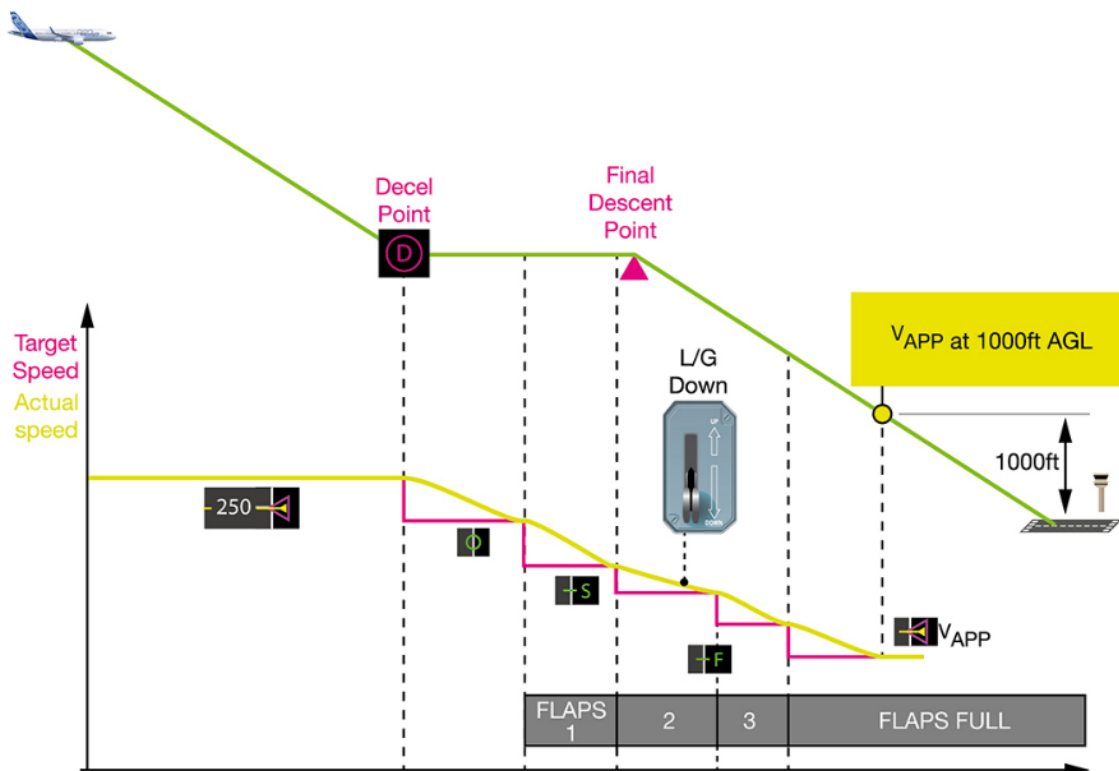


Figure 43: Typical managed descent profile (source Airbus)

During a typical descent profile an aircraft tries to reduce to the FAS just before 1000ft AGL (Above Ground Level). This reduction to FAS can be done earlier upon request from the controller (see Figure 43).

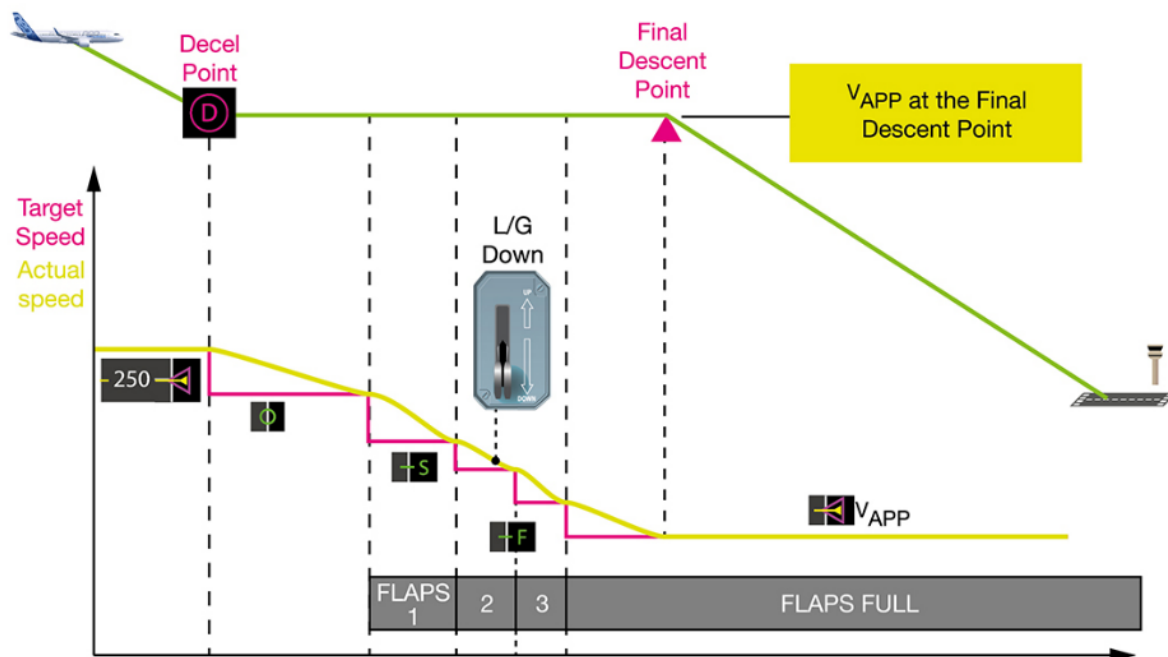


Figure 44: Early stabilized approach (source Airbus)

E.4.1.2 Speed profile on the runway

When the aircraft is landing it flares just before reaching the touchdown point, touches down and then makes a ground roll on the runway until the runway exit. The ground roll is influenced by the brake settings and sometimes by the exit choice. Even in case ATC has a preferred (high-speed) exit to be used it is up to the flight crew to decide to really take that exit, a decision generally based on safety considerations. However ATC may ask and instruct to quickly vacate the runway.

The speed profile during the landing roll depends on the aircraft performance characteristics, environmental conditions, the runway condition and the airline operational procedures.

E.4.1.2.1 Aircraft performance characteristics

The aircraft performance characteristics influence the speed profile of the ground roll of the aircraft during landing. Depending on the aerodynamic drag, remaining aerodynamic lift, brake settings, and the aircraft weight the aircraft decelerates at a specific level.

The aerodynamic drag and remaining aerodynamic lift are determined by the flap, airbrake and spoiler settings. Further braking is done using thrust reversing and wheel brakes. The effectiveness of the flaps, airbrakes, spoilers, and thrust reversing is speed dependent. The effectiveness of the wheel brakes is dependent on the runway condition and the remaining aerodynamic lift. They both influence the available friction.

E.4.1.2.2 Environmental and runway conditions

Environmental conditions can be split into static and dynamic elements:

- Static
 - Runway. The runway heading influences how the wind affects the aircraft aerodynamic performance, like drag and remaining lift. The runway length and locations of exits influence where aircraft can exit. The runway slope has also influence on the landing roll.
 - Runway exit. The type of runway exit determines the maximum exiting speed. To illustrate, a high speed runway exit at a 30 degree angle to the runway allows for a higher exit speed than an exit with a straight 90 degree angle to the runway.
- Dynamic
 - Wind conditions influence the ground speed of the aircraft on final approach. This influences the ground speed of the aircraft upon touchdown.
 - Runway surface conditions (dry, wet, ice, snow, etc) influences the braking action and therefore the needed rollout length and achievable runway exits.

E.4.1.2.3 Operational procedures

During the ground roll the aircraft crew reduces speed to a speed that allows the runway exit to be taken, and then exits the runway. During the ground roll the aircraft uses thrust reversers, airbrakes and/or spoilers. Furthermore, the flap setting influences the aerodynamic drag. The wheel brakes are usually only used at lower speeds to prevent overheating. The braking systems can be activated by the flight crew or can be automatically activated upon touchdown. Below certain speeds thrust reversing, airbrakes and spoilers will be deactivated by procedure. This is due to its reduced effectiveness at low speeds, and for thrust reversing also due to the possibility for engine-damage. Then only wheel braking remains available. The airline policies determine how the braking systems are used. The flight crew can adapt the braking to aim for a specific runway exit.

The typical braking schedule is as follows:

- Main gear touchdown
- Air brakes activated
- Front wheel touchdown
- Reverse thrust activated (can be before front wheel touchdown)
- Reverse thrust is deactivated below around 60/80 kts.
- Air brakes are deactivated below around 30/40 kts.
- Coasting at a reasonable speed until runway exit
- Wheel braking to a safe speed to exit the runway.

E.4.1.2.4 Runway Occupancy Time

The runway occupancy time (ROT) during landing is the time between crossing the threshold of the runway and exiting with the tail the runway safety area or ILS critical area. Note that currently there is no internationally accepted definition on ROT but the one here provided is applied.

During ILS CAT I conditions it is only necessary to exit with the tail the runway safety area. During ILS CAT II/III conditions the ILS critical area has to be exited with the tail.

The speed profiles during the descent over the threshold, the flare until touchdown, and ground roll until full exit determine the runway occupancy time.

E.4.1.3 Separation evolution

The separation between successive aircraft on final approach depends on the starting conditions, the speed profiles of the aircraft, and the time to exit the runway.

E.4.1.3.1 Starting conditions

Before an aircraft is on final approach the approach controller can influence the separation between subsequent aircraft on final by requesting a specific indicated airspeed (IAS), and by adjusting where an aircraft is turning towards the base and final approach. This is called tromboning, see Figure 44.

The interception altitude where an aircraft intercepts the ILS glideslope can be dependent on the side the aircraft is on downwind. This is done to keep aircraft vertically separated when aircraft fly towards each other on base.

This influences the starting conditions of an aircraft on final approach. This means that an aircraft starts the final approach at a specific time, at an initial distance from the threshold, at an initial interception altitude with an initial (ILS) intercept heading and at an initial airspeed.

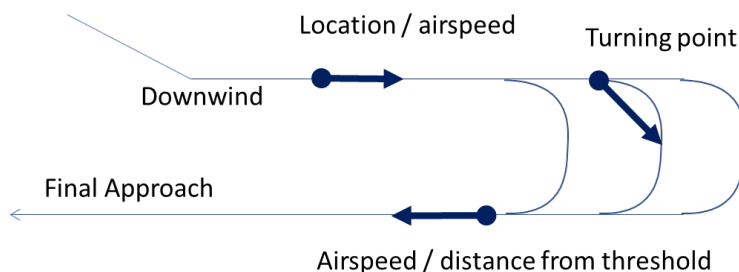


Figure 45: Tromboning

E.4.1.3.2 Separation during landing

When two aircraft are approaching a runway in general the distance separation between the two aircraft will decrease over time (see Figure 45). This is due to the fact that aircraft are slowing down on final approach or due to the fact that the following aircraft has an overall faster speed profile than the leading aircraft. Therefore, in most cases the smallest separation distance is to be expected when the leading aircraft is at the end of the final approach (e.g. threshold).

Only when the leading aircraft has a considerable faster speed profile on final approach compared to the following aircraft it may be the case that the smallest distance separation is at the start of the final approach of the following aircraft.

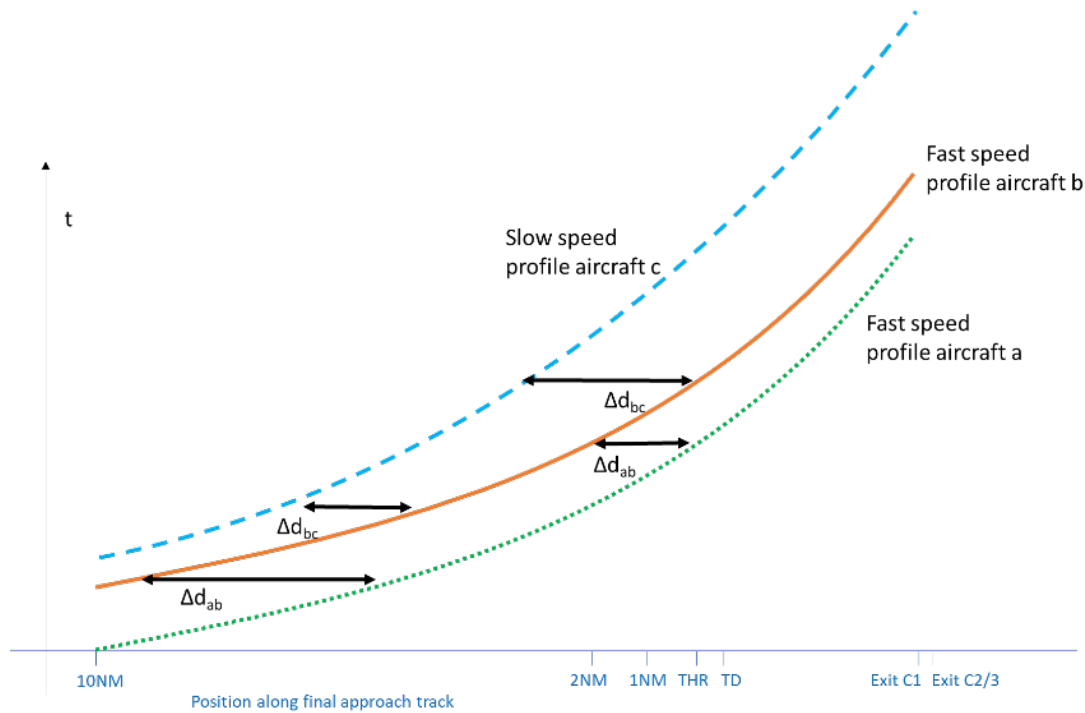


Figure 46: The distance separation (Δd) varies along the final approach track dependent on the difference in speed profiles of subsequent aircraft.

For the time separation between successive aircraft the separation behaviour is different (see Figure 46). When aircraft have similar speed profiles the time separation stays the same during the final approach. Even if both aircraft reduce speed over time. When the aircraft have different speed profiles the time separation can decrease or increase along the final approach.

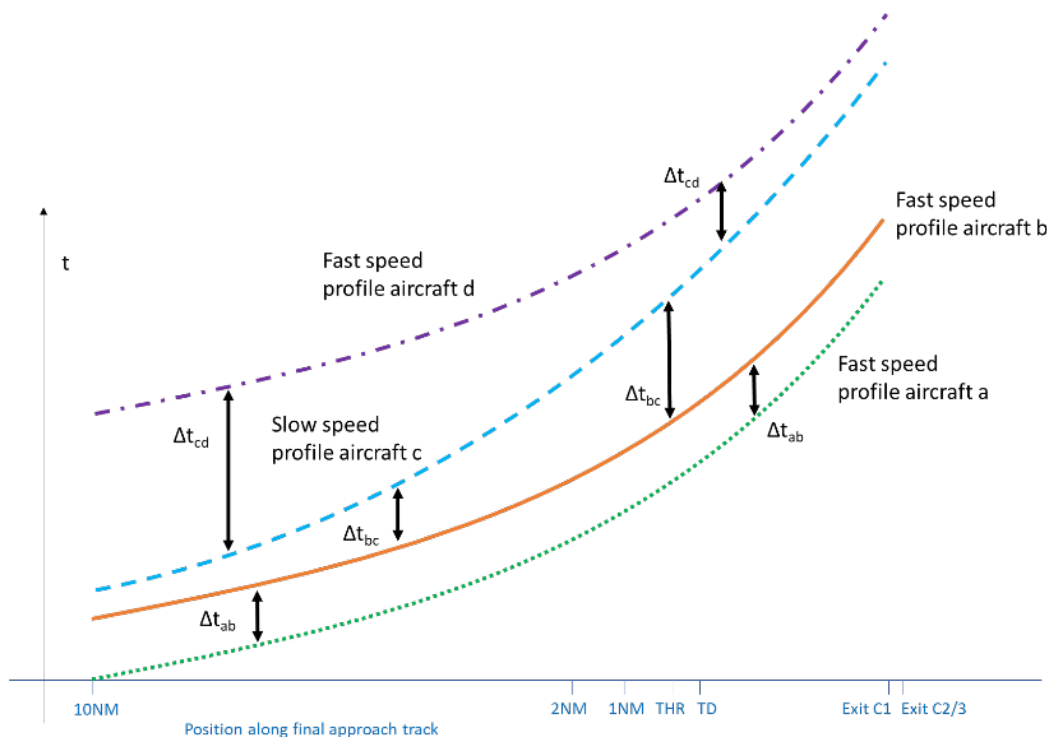


Figure 47: The time separation (Δt) varies along the final approach track dependent on the difference in speed profiles of subsequent aircraft.

The approach controller can have a limited influence on the speed profile by requesting an early reduction to final approach speed (see Figure 43).

E.4.1.4 Minimum Separation

The minimum separation between subsequent aircraft is dependent on three elements: the minimum radar separation, the minimum wake turbulence separation and the minimum required separation upon exiting the runway.

E.4.1.4.1 Minimum Radar Separation

The Minimum Radar Separation (MRS) is a surveillance system given and applicable between succeeding aircraft on the final approach track within the 10 NM to the runway threshold. The MRS is applicable until the crossing of the threshold of the leading aircraft. Typically the minimum radar separation is 3 NM, like currently at AAS. ICAO allows for reducing the MRS to 2.5NM or even lower. For this the ANSP at an airport must show compliance with specific conditions including systematic low ROTs. A MRS of 2.5 NM is already operational at several European airports including Heathrow airport. For certification for MRS 2.5 ICAO demands proof through data collection, statistical analysis and theoretical modelling that the runway occupancy time (ROT) is low enough. Also, there are requirements regarding the performance of the surveillance system.

E.4.1.4.2 Minimum Wake Turbulence Separation

Aircraft that create lift produce a wake vortex turbulence behind the aircraft. This turbulence can be dangerous to following aircraft. The turbulence decays over time to non-dangerous levels. To prevent wake encounters a separation needs to be applied to subsequent aircraft. The wake vortex separation is normally based on ICAO wake turbulence category minima. Alternatively it can be based on special wake vortex separation minima like in RECAT-EU (Wake Turbulence Recategorization) or as derived in RECAT-EU- PWS. Wake vortex minima can be distance or time based. Not for all aircraft pairs a dedicated wake vortex minimum is provided and then generally only the MRS applies.

The distance based separation is easily identifiable by controllers using their surveillance system. Therefore the standard ICAO wake vortex minima are distance based. Headwind reduces the ground speed of aircraft, which results in an increased time separation for aircraft pairs. This reduces the effective landing rate. Using time based wake vortex separation minima the effect of headwind on the separation is taken away. This keeps the landing rate up and less dependent on the wind conditions.

After touching down the wake vortex reduces substantially as considerable less lift is generated. Therefore, the wake turbulence separation is assumed to be applicable until the touchdown point of the leader aircraft.

E.4.1.4.3 Minimum Separation upon Exiting the Runway

The visibility conditions at an airport have influence on the minimum separation criteria for a follower aircraft with a leading aircraft during the final approach and when being on the runway.

At Schiphol during ILS Cat 1 or better conditions (ceiling above 200ft and Runway Visual Range (RVR) above 550m) a late landing clearance maybe given to a following aircraft before 1 NM from the threshold when it can reasonably be expected that the preceding aircraft has exited the runway when the following aircraft passes the threshold.

At Schiphol during ILS Cat 2/3 conditions (ceiling below 200ft or RVR below 550m) the preceding aircraft has to have exited the protected area (e.g. tail is outside Cat II/III Sensitive Area) when the following aircraft is given the landing clearance not closer than 2 NM from the threshold.

E.4.1.5 Control the separation

The approach controller must provide enough separation between subsequent landing aircraft for the complete descent and landing roll. The approach controller can influence the starting sequence and conditions of following aircraft by using restrictions in indicated airspeed, and using radar vectoring from IAF to FAF and/or tromboning to affect the turn to base and final approach (see Figure 44). This allows the controller to separate subsequent landing aircraft. Furthermore, the controller is able to request aircraft to reduce to the Final Approach Speed early (see Figure 43).

To ensure that an aircraft has exited the runway before a subsequent aircraft passes the threshold the runway controller may ask the pilot of the aircraft on the runway to quickly vacate the runway. It is up to the pilot to comply with this request.

E.4.2 Forecasting landing operations

E.4.2.1 Forecasting flight time to threshold

To be able to forecast the flight time to the runway threshold data regarding two categories is available:

- current status aircraft
- current environmental and runway conditions

E.4.2.1.1 Forecast

The objective is to forecast the flight time of the flight from the current aircraft position to the runway threshold. A machine learning model will provide the forecast. For the training phase of a machine learning model it is necessary to provide also the realized flight time.

E.4.2.1.2 Current status aircraft

- Time of location data (Local Time)
- Aircraft type (ATC system)
- Airline (ATC system)
- Location of aircraft relative to the landing runway
 - Distance from threshold (surveillance)
 - Lateral deviation from extended center line (surveillance)
 - Altitude (Mode C)
 - Approach fix (ATC system)
- Speed of aircraft
 - Ground Speed (estimated by surveillance system)
 - Assigned Speed (Indicated Airspeed) (ATC system)
 - True Airspeed (ATC system)
 - Descent rate (estimated by surveillance system)

E.4.2.1.3 Current environmental and runway conditions

- Static data
 - Runway
 - Runway exit locations
 - Runway exit types
- Dynamic data
 - Uniform Daylight Period (ATC system)
 - Visibility conditions (Good/Marginal/BZO-A/B/C/D) (ATC system)
 - Current Headwind measured at Runway (ATC system)
 - Headwind average 3/15 minutes (ATC system)
 - Crosswind measured at Runway (ATC system)

- Crosswind average 3/15 minutes (ATC system)
- Temperature measured at Runway (ATC system)
- Visibility measured at Runway (ATC system)
- Wind Variability measured at Runway (ATC system)
- Wind Gust measured at Runway (ATC system)
- Pressure measured at Runway (ATC system)
- Precipitation Type (Weather forecast)
- Precipitation Amount measured at Runway (ATC system)
- Ceiling (Weather forecast)
- Dew Point (Weather forecast)
- Peak Traffic: Inbound peak, outbound peak, night, off-peak (ATC system)
- Number of arrivals in last 20 minutes on this runway (ATC system)

E.4.2.2 Forecasting Runway Occupancy Time

To be able to forecast the Runway Occupancy Time data regarding two categories is available:

- current status aircraft
- current environmental conditions

E.4.2.2.1 Forecast

The objective is to forecast the Runway Occupancy Time of the flight given the current position before the runway threshold. A machine learning model will provide the forecast. For the training phase of a machine learning model it is necessary to provide the realized Runway Occupancy Time.

E.4.2.2.2 Current status aircraft

- Time of location data (Local Time)
- Aircraft type (ATC system)
- Airline (ATC system)
- Location of aircraft relative to the landing runway
 - Distance from threshold (surveillance)
 - Lateral deviation from extended center line (surveillance)
 - Altitude (Mode C)
 - Approach fix (ATC system)
- Speed of aircraft
 - Ground Speed (estimated by surveillance system)
 - Assigned Speed (Indicated Airspeed) (ATC system)
 - True Airspeed (ATC system)
 - Descent rate (estimated by surveillance system)

E.4.2.2.3 Current environmental conditions

- Static data
 - Runway
 - Runway exit locations
 - Runway exit types
- Dynamic data
 - Uniform Daylight Period (ATC system)
 - Visibility conditions (Good/Marginal/BZO-A/B/C/D) (ATC system)
 - Current Headwind measured at Runway (ATC system)
 - Headwind average 3/15 minutes (ATC system)
 - Crosswind measured at Runway (ATC system)
 - Crosswind average 3/15 minutes (ATC system)
 - Temperature measured at Runway (ATC system)
 - Visibility measured at Runway (ATC system)
 - Wind Variability measured at Runway (ATC system)
 - Wind Gust measured at Runway (ATC system)
 - Pressure measured at Runway (ATC system)
 - Precipitation Type (Weather forecast)
 - Precipitation Amount measured at Runway (ATC system)
 - Ceiling (Weather forecast)
 - Dew Point (Weather forecast)
 - Peak Traffic: Inbound peak, outbound peak, night, off-peak (ATC system)
 - Number of arrivals in last 20 minutes on this runway (ATC system)
 - Planned gate or platform (ATC system)

E.4.2.3 Forecasting rolling time to runway exit

To be able to forecast the rolling time to the runway exit data regarding two categories is available:

- current status aircraft
- current environmental conditions

E.4.2.3.1 Forecast

Forecasted rolling time of the flight from the current position to the runway exit.

For a machine learning method it is necessary to know the realized rolling time.

E.4.2.3.2 Current status aircraft

- Time of location data (Local Time)
- Aircraft type (ATC system)
- Airline (ATC system)
- Location of aircraft relative to the landing runway
 - Distance beyond the threshold (surveillance)

- Speed of aircraft
 - Ground Speed (estimated by surveillance system)

E.4.2.3.3 Current environmental and runway conditions

- Static data
 - Runway
 - Runway exit locations
 - Runway exit types
- Dynamic data
 - Uniform Daylight Period (ATC system)
 - Visibility conditions (Good/Marginal/BZO-A/B/C/D) (ATC system)
 - Current Headwind measured at Runway (ATC system)
 - Headwind average 3/15 minutes (ATC system)
 - Crosswind measured at Runway (ATC system)
 - Crosswind average 3/15 minutes (ATC system)
 - Temperature measured at Runway (ATC system)
 - Visibility measured at Runway (ATC system)
 - Wind Variability measured at Runway (ATC system)
 - Wind Gust measured at Runway (ATC system)
 - Pressure measured at Runway (ATC system)
 - Precipitation Type (Weather forecast)
 - Precipitation Amount measured at Runway (ATC system)
 - Ceiling (Weather forecast)
 - Dew Point (Weather forecast)
 - Peak Traffic: Inbound peak, outbound peak, night, off-peak (ATC system)
 - Number of arrivals in last 20 minutes on this runway (ATC system)

E.4.2.4 Forecasting separation

There is a need to forecast the separation between subsequent aircraft. Especially forecasting the position of the following aircraft at the moment the leading aircraft will reach (1) the runway threshold, and (2) the leading aircraft has exited the runway.

The following separation forecasts need to be generated:

1. Forecast the separation of subsequent aircraft at the moment in time the leading aircraft will reach the runway threshold given the current status of both aircraft.
2. Forecast the separation of subsequent aircraft at the moment in time the leading aircraft will have exited the runway given the current status of both aircraft.

For a machine learning method it is necessary to know the realized separation when the leading aircraft reaches the runway threshold, and the runway exit.

The separation between two subsequent aircraft can be viewed as distance or time difference between two independent flights. In practice subsequent flights are not independent when they are expected to get close to the separation minima.

When the separation is expected to go below the allowable minima it is necessary for the controller to take adequate action. If no solution is available to resolve the separation issue the following aircraft needs to be taken out of sequence and make a go-around. The controller can resolve the separation issue by requesting the leading aircraft to not exit late on the runway, and/or the following aircraft to reduce to the FAS early.

Currently, there is no data available regards given voice commands to pilots to understand the effects of controller commands on the separation.

E.5 Methodology

E.5.1 Defining TTF and ROT

The current study focuses as a first step on predicting the TTF and ROT at the 4 NM to threshold point. The 4 NM point was chosen for several reasons. First of all procedures prescribe that on final approach aircraft maintain 160 kts until 4 NM before threshold. From 4 NM onwards the aircraft decelerates to the FAS. However, it is known that not all pilots can always comply with this rule and sometimes the deceleration is initiated at an earlier point in time. The point at which deceleration is initiated is an important factor in for example the TTF. By predicting at the 4 NM it is ensured that the aircraft has initiated deceleration.

In short, closer to the runway threshold predictions are expected to be more accurate. However, 1 or 2 NM to the threshold would be too late for the pilot or ATCO to make meaningful changes to the path or speed of the aircraft. The 4 NM is still far enough from the threshold for ATC's to issue useful instructions to pilots such as expedite a reduction to FAS or to initiate a missed approach.

In the next section the concepts of ROT and TTF are defined in the context of this study and project. The ROT value used and the TTF value calculated in this study is dependent on the data on which it is based and the way this data is generated by LVNL.

E.5.1.1 Time-To-Fly

The TTF is defined as the time it takes an aircraft to reach the runway threshold from a given distance from the runway threshold. The TTF is considered an important parameter for a runway controller, since it describes the time required for an aircraft to land at the runway. Knowing this information can be especially useful for a controller that must issue landing and take-off clearances for consecutive operations. During such operations consecutive landings and take-offs should be commenced as efficiently and safe as possible. Figure 47 shows the distribution of the TTF from 4 NM to threshold in this study.

Also, on Schiphol, during certain environmental conditions the timing of operations is required. Timing of operations describes the need to precisely time the issuing of take-off and landing clearances at a set time. The TTF of an arriving aircraft can be of importance for an aircraft on a different converging runway and/or aircraft on the same runway during mixed mode operations (i.e. a single runway that is used for both take-off and landing operations).

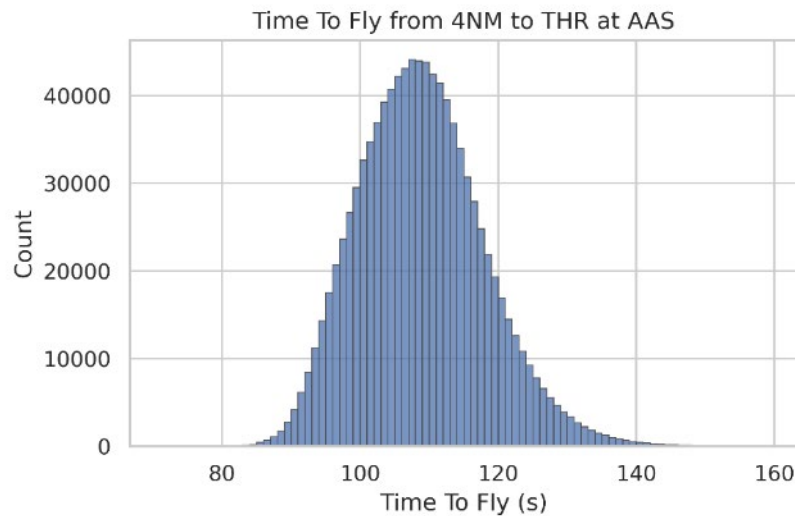


Figure 48: Distribution of the TTF at Schiphol airport

E.5.1.2 Runway Occupancy Time

The runway occupancy time parameter describes the duration that an aircraft occupies the runway. The ROT during the landing phase is defined as the difference between the time an aircraft exits the runway and the time it crosses the runway threshold. In the context of this study, the time of runway exit is defined as the moment the spacing between the aircraft track and the runway centreline first exceeds 90 meters. This definition is chosen as it was the default for the algorithm of LVNL that generated the dataset which was used for the modelling in this project. Figure 48 shows the distribution of the ROT in the data that was used in the study.

It should be noted that the track data of aircraft is a collection of radar reflections which have been aggregated by a tracker system. These positions are determined by interrogating the transponder of the aircraft. The track data used in this study results from interrogations of the aircraft's transponder. Eventually, the positions that are in the track data are the reflections of the transponder of the aircraft, which can be in situated in any part of the aircraft's fuselage. This variance in the position of the transponder in the fuselage causes a degree of uncertainty in the measurement of the actual position of the aircraft by the radar system.

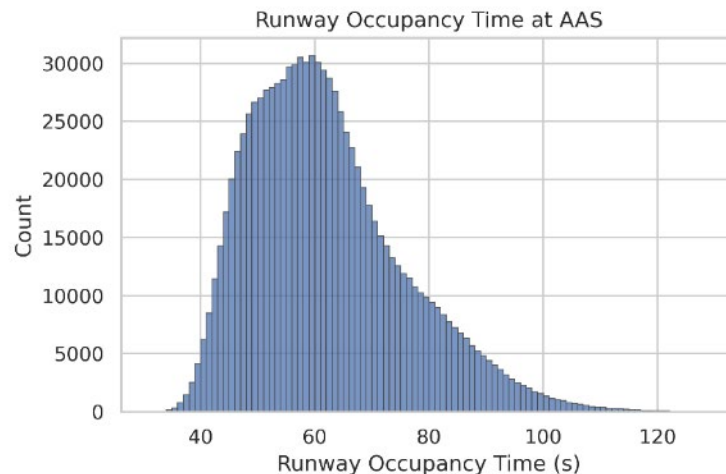


Figure 49: Distribution of the ROT at Schiphol airport.

E.5.2 Data

As indicated before the data used in this project was received from LVNL. LVNL provides tower, approach and area control to both Civil and Military aircraft in the civil airspace of The Netherlands. Moreover, LVNL also provides Flight Information Control in selected airspace. The provided dataset is based on track data of the ARTAS (ATC Radar Tracker And Server) tracker system of LVNL from the time period of January 2016 – June 2021. In addition, LVNL integrated a number of additional parameters in the dataset such as the total number of movements in the last hour, aircraft type data and aircraft RECAT type. The full feature set used in the modelling will be discussed in section E.5.2.3. In addition, weather data features have been added at a later stage.

The dataset provided by LVNL contains information per flight from 10 NM before runway threshold, up until runway threshold. By use of spatial analysis the time stamps and other relevant information from the mode-S (i.e. ground speed and altitude) have been extracted at evenly spaced specific points per NM, along the approach and landing path. For the point to be logged the aircraft heading was required to be within a limited margin of the runway heading, thereby guaranteeing that all flight tracks in the dataset were properly aligned with the runway. Finally, the ROT was logged with a distance to threshold value of -1. Note that this -1 does not refer to a distance but merely serves as a reference.

E.5.2.1 Features included

Table 29 shows the features in the dataset after the pre-processing steps described in section E.5.2.3. for both the TTF and ROT models. In the TTF prediction, models were developed for two different data sets in which different numbers of features were included. In the first set only features from the time of the 4 NM inference point were used. In the second set features from the point previous to the inference point were added, at 5 NM to threshold. In addition, the difference in ground speed between the 4 and 5 NM point was added as a feature.

The x and y features in this dataset were defined as x and y coordinates as part of a custom Schiphol grid that is used by LVNL. The coordinate (0, 0) is located in the vicinity of the main Schiphol control tower, which is approximately situated in the centre of the airfield.

For the ROT prediction, models were developed for two cases. In the first case the runway exit feature was not included in the feature set and in the second case the runway exit feature was included. Including the runway exit as a feature in the dataset was done to study the ideal hypothetical situation where the runway exiting behaviour of aircraft is known with absolute certainty. Predictable runway exiting behaviour can be achieved when airports have defined which runway exits are preferred for specific aircraft types and also communicate these guidelines to the aircraft operators.

Also, previous studies have shown that having information about which runway exit will be used has a large influence on the performance of the model [E.4]. Other factors, such as the runway exit angle and position can also influence the ROT. By including the runway exit an upper bound on the model's performance can be determined in the case that the runway exiting behaviour is highly predictable.

Feature	Description	Example values	Cardinality
AC_TYPE	Aircraft type according to ICAO Doc. 8643	E75L, B738, E190, ...	40
WTC	ICAO WTC category	L, M, H, J	4
RECAT	RECAT-EU wake turbulence category.	A, B, C, D, E, F	6
RW	Runway used for landing.	18R, 06, 18C, 36R, 27, 36C, 22	7
STACK	Intermediate Approach Fix used to enter TMA Schiphol	ARTIP, RIVER, SUGOL	3
RWC	Current runway combination that is in use	06 / 36C, 18C / 24, ...	145
BAANCONFIG	Number of runways in use for both take-off and landing	1+1, 2+1, 1+2, 2+2	4
UDP	Universal daylight period	0, 1	2
zicht	Special visibility conditions	'MARGINAL', 'GOOD', 'BZO-A', 'BZO-B', 'BZO-C', 'BZO-D'	6
HEADWIND	Headwind at the runway	6.6 m/s	-
CROSSWIND	Crosswind at the runway	5.5 m/s	-
PIEK_TYPE	Type of traffic peak at the time of the flight	OFFPEAK, INBOUND, OUTBOUND, NIGHT	4

Feature	Description	Example values	Cardinality
D20M	Number of arrivals in the past 20 minutes at AAS	14	-
D20M_RW	Number of arrivals in the past 20 minutes at runway	10	-
D60M	Number of arrivals in the past 60 minutes at AAS	40	-
D60M_RW	Number of arrivals in the past 60 minutes at runway	25	-
weekday	Day of the week.	0, 1, 2, ...	7
month	Month of the year	1, 2, 3, ...	12
hour	Hour of the day	0, 1, 2, ...	24
year	year	2016, 2017, ...	5
x_p_4 ¹	x coordinate at inference point	-209.05	-
y_p_4 ¹	y coordinate at inference point	695.21	-
fl_p_4	Flight level at inference point	12.2	-
h_p_4	Height in feet	1327.29 ft	-
gs_p_4	Ground speed in knots at inference point	151.0 kts	-
ri_regenm_10	Precipitation density in mm per hour	0.0	-
t_dryb_10	Temperature in degrees Celsius	8.4	-
x_p_5 ¹	x coordinate 1 NM before inference point	-201.58	-
y_p_5 ¹	y coordinate 1 NM before inference point	822.98	-
fl_p_5 ¹	Flight level 1 NM before inference point.	16.0	-
h_p_5 ¹	Height 1 NM before inference point in feet	1651.79	-
gs_p_5 ¹	Ground speed 1 NM before inference point in knots	164.09	-

Feature	Description	Example values	Cardinality
dv_gs ¹	Difference in ground speed between 4 and 5 NM	12.04	-
gate	Gate that was assigned to the aircraft	H01, H02, ...	217
baai	Aircraft stand bay that was assigned to the aircraft	B-apron, C-D, ...	15
rw_exit ²	Exit that the aircraft takes to vacate the runway	V1, V2, V3, ...	45

Table 29: Features used in both the TTF and ROT prediction. The TTF and ROT columns indicate whether these features were present in the TTF and ROT datasets. Features with a ⁽¹⁾ are used for TTF modelling. Feature indicated with a ⁽²⁾ were only present in subset of the ROT models.

E.5.2.2 Analysis

The dataset as provided by LVNL covered the traffic period from 1st of January 2016 to 29th of February 2020 and consisted of a total of 13,288,343 rows of data. Each row of data represented a sample of a flight, logged at a position during the final approach and landing. The next subsections describe some more information regarding the contents of the dataset.

E.5.2.2.1 General Statistics

Table 30 describes the number of samples per point along the final approach path in the provided dataset, before pre-processing steps such as removing go-arounds. It can be seen that the number of points increases as the distance to threshold decreases. This is expected, as aircraft at Schiphol can be vectored towards the runway less than 10 NM before the threshold. Only samples in which the aircraft is properly aligned with the runway heading are included, and vectoring can cause an aircraft to be not aligned with the runway until a short distance to threshold. Still, the number of samples indicated at point -1 are of a lower number than the number of samples at point 0, which denotes the runway threshold. The reason for this is probably that the algorithm was not able to determine which runway exit was used.

Point (NM)	Number of Samples
-1	1135308

0	1169515
1	1164698
2	1164398
3	1162968
4	1159134
5	1155939
6	1146524
7	1130528
8	1084917
9	979240
10	835174

Table 30: Distance to threshold in NM and the number of flights for which a sample at this distance to threshold was available. Note that -1 is the sample that denotes the runway exit and does not represent a distance.

Table 31 shows the number of samples per year. The effect of Covid-19 can be clearly seen in the years of 2020 and 2021. Please note that the year 2021 is only partially included in the dataset.

Year	Number of Samples
2016	244925
2017	253297
2018	255133
2019	253784
2020	117207
2021	45169

Table 31: Number of samples per year in the dataset provided by LVNL.

E.5.2.3 Pre-processing

Before training the models a number of pre-processing steps were applied to the data. First, additional information was added to the dataset, so a single record included all the necessary information for modelling. This included adding the information from the 4 NM point to the ROT dataset. For the TTF model the information of both the 4 NM and 5 NM point were added to the dataset. Subsequently additional weather data such as outside air temperature and wind were added. Both these data were

retrieved from the KNMI Data Platform [E.5] that were recorded at a weather station at AAS near runway 18C.

As mentioned before, the data that was used in the study ranged from 1st of January 2016 to 29th of February 2020. Flight tracks from 1st of March 2020 onwards were omitted to exclude abnormal operating conditions related to the COVID-19 pandemic. Outliers were excluded in both the TTF and ROT prediction models. In TTF, all flights with a TTF larger than 160 seconds were considered to be outliers. For ROT, all landings with a ROT smaller than 30 seconds and larger than 140 seconds were considered outliers and removed from the dataset. In addition, flights where the time difference between the 4 NM point and the runway exit time was larger than 250 s were also considered to be outliers and thus removed.

Missed approaches are filtered out as these lead to wrong TTF values and returning flight ids, which may cause inconsistencies when joining data. It was chosen to only include flights from the top 40 most occurring aircraft types. These were also the aircraft types for which more than 1000 flights existed in the dataset. The year, month, hour and day of the week and year at the 4 NM inference point were added as features.

The IAS (Indicated Airspeed) and TAS (True Airspeed) were only available in data from after a certain date. Therefore, it was decided to exclude these features. Weather data was considered to be missing if the time difference between the 4 NM inference point time and the time of closest available weather measurement was less than one hour. Samples with missing values were deleted. The final TTF dataset consisted of 1.001.877 and 1.000.062 samples for the dataset without and without 5 NM data respectively. For the ROT dataset the total number of flights after pre-processing was 958.651.

Models such as random forests require the encoding of categorical into numerical features. The encoding of features can be done in a number of ways, such as label encoding and one-hot encoding. In label encoding the categorical feature is replaced by an integer. For example, each of the 40 aircraft types in the dataset was replaced by a number in the range of 0 to 39. In the ordinal categorical features 'WTC, RECAT and zicht (visual conditions)', the order is taken into account in assigning the integer encoding values. One-hot encoding is a method that is said to improve performance when encoding non-ordinal categorical features. Preliminary results showed that one-hot encoding offered no advantage in terms of performance, and therefore label encoding was used in the rest of the study.

E.5.2.4 Train-validation-test split

Hold-out validation was used for selecting the optimal model and assessing the model performance. In hold-out validation, the data is split into a training, validation and test set. The training set is used to train the model. The validation set is used to find the optimal hyperparameters. Hyperparameters are the variables that affect the learning process and performance of the model that are not learned from the data but are directly provided to the model. For random forests, an example of a hyperparameter would be the number of estimators in the forest. The test set consists of data that was not used in the training process and is used to give a final estimate of the performance of the model on unseen data [E.6].

The validation and test were randomly sampled from the final 12 months of data, using a 1:1 distribution. All samples before to the final 12 months of data, i.e. previous to 2019-03-01 were used as training data. This was done for a number of reasons. First, by sampling the test data from the last

year of the dataset the test data is likely to be more representative of future data the model will make predictions on. Changing procedures and circumstances around the airport can influence model performance. Second, by sampling from a full year of data increases the likelihood that all possible circumstances and seasonal effects are represented in the test set. Finally, sampling the validation and test set from the same distribution will ensure that the performance on the validation set is indicative of the performance on the test set.

E.5.3 Model

E.5.3.1 Decision trees

Decision tree algorithms can be applied to both classification and regression problems. This study only uses regression models. In decision tree algorithms a predictor space is divided into a number of regions. The predicted value $f(x_i)$ of the model f for a given sample i is the mean of the target variable y of the samples from the training set that belong to the same region of the predictor space [E.6].

This predictor space is divided into regions by a greedy algorithm. At each iteration of the algorithm the model selects a split from a set of all possible splits and adds this to the model. A score or cost is calculated for every leaf node, every feature and every possible value of the feature to split on. The split that causes the largest decrease in the overall cost is added to the model. The most often used criterion or score in regression trees is the MSE (mean squared error), and was also used in this study:

$$MSE = \frac{1}{n} \sum_i^n (y_i - f(x_i))^2$$

where n is the number of samples over which the MSE is calculated.

E.5.3.2 Random forests

The machine learning algorithm that was used in this study was the random forest. In random forests a prediction is made by averaging over the prediction of a collection of decision trees. Decision trees are high variance estimators, meaning that these models tend to overfit the data. Overfitting can be explained as the case where models include the random fluctuations that were present in the training set in predictions. Random forests reduce overfitting by averaging over a large number of uncorrelated decision trees.

Reducing the correlation between the trees is done through two methods. The first method is by training the different decision trees on different versions of the training set. These different versions of the training set are generated through a process that is known as bootstrap sampling. In bootstrap sampling, n samples are drawn at random and with replacement from the original set of n samples. By doing this, in each new version of the training set only $2/3$ of the samples in the original training set are used on average in the training of each decision tree. Because the trees are trained on different training sets, the trees become less correlated.

The second method is by randomly choosing a subset features in each iteration of the training algorithm which the model is allowed to consider for the next split. In practice however, regression

models tend to perform better when all features are considered in every split and this hyperparameter is more relevant in classification problems.

Some additional hyperparameters of the model that can be considered are the maximal depth of the trees and the minimum number of samples in each leaf node. By limiting the maximal depth or increasing the minimum number of samples in each leaf, both methods result in more samples in each leaf node, averaging out over samples and should therefore reduce variance for the individual decision trees. This study makes use of the random forest regressor implementation of the sci-kit learn Python library [E.7].

E.5.3.3 Feature importance

Random forests are relatively well-interpretable models. Feature importance refers to techniques that determines which model input features are useful in predicting a certain target variable. Hence which inputs effect the predicted output the most in relative order. The feature importance can be calculated using different methods. In this study the feature permutation method was used.

In feature permutation the importance of a feature is expressed as a decrease in model performance, which in this study was expressed as a decrease in MSE. In order to find the importance of a given feature, the feature values are randomly shuffled across the samples in the dataset that is used for the evaluation. The dataset with the permuted feature is fed to a trained model. When the values of a feature are shuffled the model will not be able to make accurate predictions based on this feature, and subsequently a decrease in the model performance is expected. This procedure is repeated for all features. Features of high importance are expected to cause a large decrease in model performance.

Permutation importance can be misleading for strongly correlated features. When one of two strongly correlating features is left out, the decrease in model performance is not very large as information about the left-out feature is still available to the model through the correlating feature. This can lead to the feature importance judging two strongly correlating features as low importance features, when both features were left out the models' performance could drop significantly.

Impurity-based feature importance is an alternative method for determining the importance of the features. However, impurity-based feature importance is biased towards high-cardinality features, and since the dataset contains a number of high-cardinality features it was decided to use permutation feature importance. Moreover, preliminary results showed that impurity and permutation feature importance yielded qualitatively similar results.

E.6 Results

E.6.1 Feature importance

This section describes the resulting feature importance of both the TTF and ROT machine learning prediction models. The features importance was calculated using the models with the optimal hyperparameters and the permutation importance method was used.

E.6.1.1 TTF – without 5 NM features

Figure 49 shows the feature importance of the TTF model where features from the 5 NM to threshold point were not included in the dataset. The model was trained with the optimal hyperparameters of a minimal samples leaf of 2 and 1500 estimators.

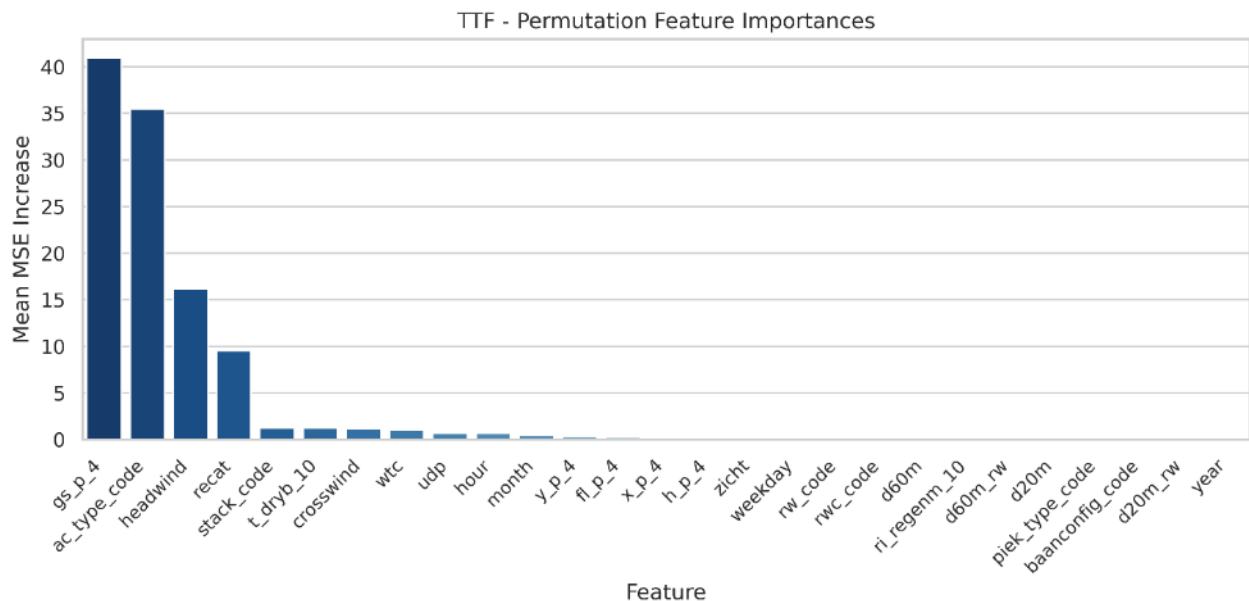


Figure 50: Feature importance of the TTF prediction model without 5 NM features.

The ground speed at the 4 NM point of inference (noted as *gs_p_4* in Figure 49, see also Table 29 for further explanations) was found to be the most important feature. This was to be expected, because the groundspeed directly determines the time necessary to cover the remaining distance to the runway threshold. Also, at 4NM DME (distance measuring equipment) aircraft are supposed to fly FAS. The FAS is generally speaking the aircraft's speed for the rest of the final approach path, up until RWY THR.

The second most important feature was found to be the aircraft type. To a large extent, the aircraft type determines the FAS of the aircraft. The FAS is based on reference speed V_{ref} of the aircraft, which depends on the mass (weight) of the aircraft and is determined by the aircraft manufacturer.

Another important feature was the headwind, as to be expected, followed by the RECAT-EU category, in which aircraft types are aggregated by wake turbulence characteristics. Larger and/or heavier aircraft tend to cause more severe wake turbulence. Larger and heavier aircraft tend to have higher final approach speeds, and therefore RECAT-EU was probably also considered as an important feature of the model, since aircraft mass (weight) itself was not part of the dataset.

The x and y coordinates can indicate how well the aircraft is currently aligned to the runway. However, at 4 NM aircraft are expected to be properly aligned with the runway centre line anyway, and therefore these are not expected to be of a high importance.

Other parameters worth mentioning are environmental factors such as headwind, crosswind and the outside air temperature. Headwind is considered an important factor since it influences the ground speed of the aircraft. Aircraft that endure much headwind generally fly with a lower ground speed and thus take longer to travel to THR. Crosswind can influence the TTF by imposing a technically more challenging approach on the pilot, prompting pilots to fly more careful and reduce to FAS earlier than the 4 NM point. Lastly, the influence of the outside air temperature on the model is more difficult to explain. The ambient air temperature influences the overall aircraft performance, causing aircraft to land faster (smaller TTF) on hot days than on cold days. The relation between TTF and headwind and temperature is visualized for the Boeing 737-800 aircraft in Figure 50.

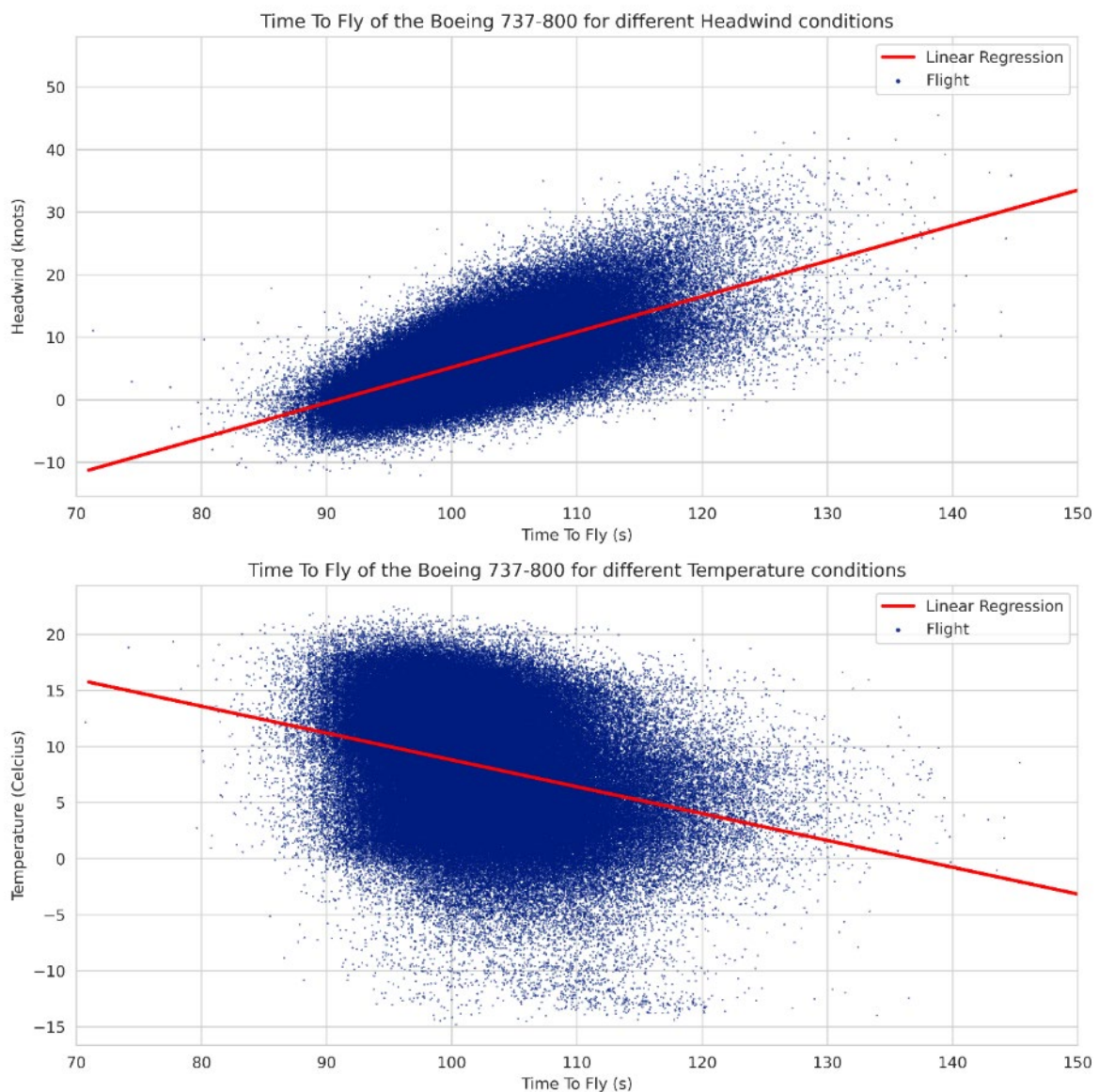


Figure 51: Headwind and temperature versus TTF plots.

Parameters that indicate the throughput on the airport were found to be of low importance (i.e. d60m, d60m_rw, d20m, d20m_rw). When an airport has to process a high number of landing and take-offs, air traffic controllers tend to instruct pilots to use higher airspeeds up until the 4NM point, as to achieve a higher number of landings per hour. However, from 4 NM aircraft are requested by ATC to fly FAS, therefore the parameters indicating how busy the airport is are expected to not be important for this model, which considered features from point 4. In the case the model were to make predictions at 6 NM or higher from the runway threshold, these parameters might be more important.

E.6.1.2 TTF – with 5 NM features

Figure 51 shows the permutation feature importance for the best scenario 2 model. This scenario, includes the parameters logged at point 5 NM in the dataset. Features recorded at the 5 NM point and the difference in groundspeed between the 5 NM and 4 NM point seem to have little influence on the model performance.

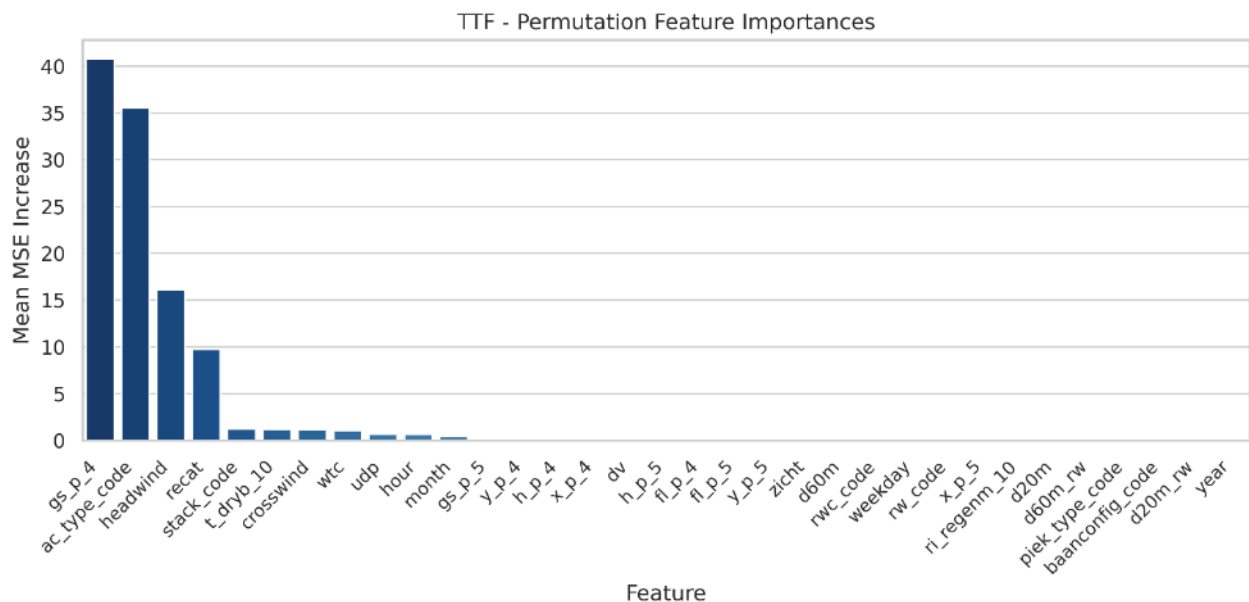


Figure 52: Feature importance of the TTF prediction model with 5 NM features.

E.6.1.3 ROT – without runway exit

Figure 52 shows the feature importance of the ROT machine learning prediction model where the runway exit was not included in the features. The model was trained with a minimal samples per leaf of 5 and a total of 1000 estimators. It can be seen that the most important feature for the ROT prediction is the RECAT-EU category of the aircraft. This is likely due to the fact that the RECAT category and aircraft mass (hence FAS) are correlated. Larger and heavier aircraft tend to produce more wake, and they also require more runway length to slow down on the runway. Figure 53 shows the distribution of the ROT for different aircraft types.

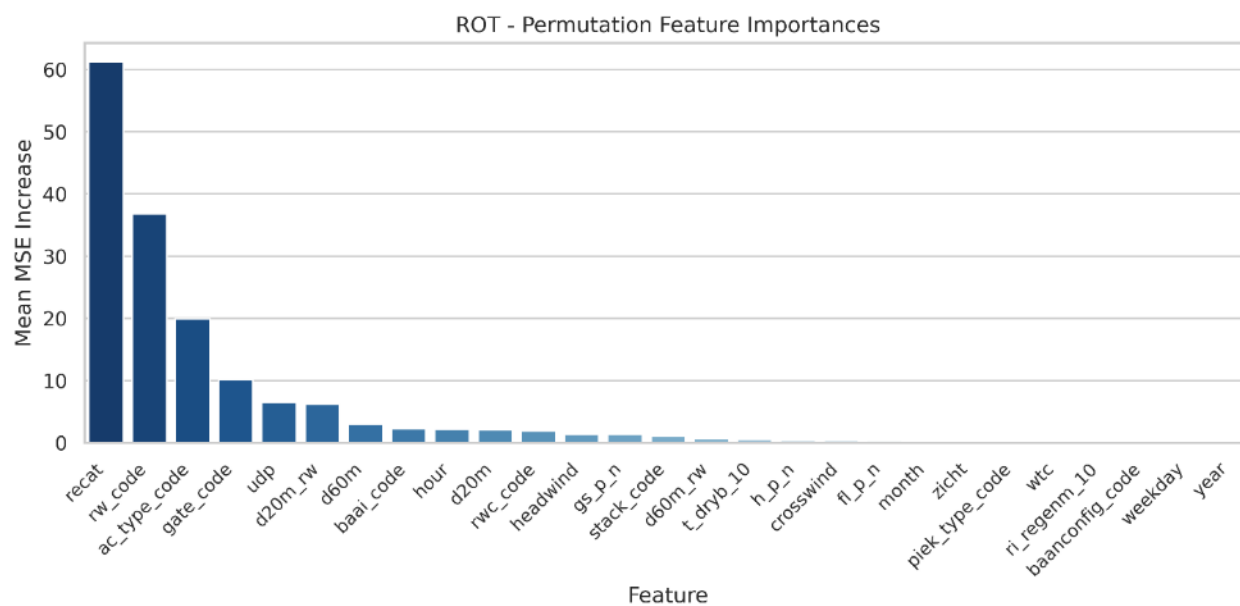


Figure 53: Feature importance of the ROT prediction model where the runway exit was not included in the features.

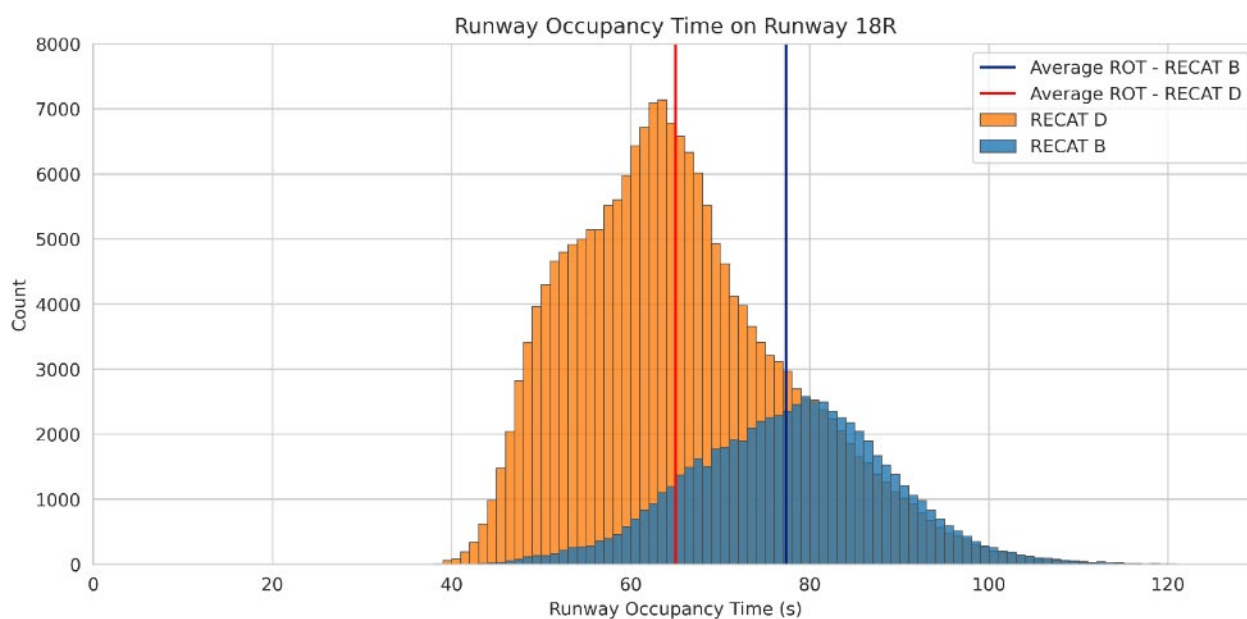


Figure 54: Distribution of the ROT for different RECAT types.

The second most important feature is the runway in use followed by aircraft type as third. The runway used is an important feature as for each runway the length is different and the exits are located at different positions. The aircraft type is also an expected important feature, as the aircraft's designed braking performance is primarily bound to the aircraft type. Of course, other factors influence aircraft braking as well, such as the availability of anti-skid systems, runway condition (i.e. dry, damp or wet).

Other infrastructure related features such as the planned parking position of the aircraft (gate_code), the bay that this gate is situated in (baai_code) and the runway on which the aircraft landed (rw_code), are also relevant. The rw_code was expected to show more relevance to the ROT, as the available runway exits determine where an aircraft can exit. The reason that the runway code was not considered to be the most relevant feature probably has to do with the fact that the runway exits at AAS are mostly all situated in a way that there is no runway that has a particular low or high ROT performance. In other words, the ROT performance of all the runway is comparable.

Environmental factors such as UDP (Universal Daylight Period) time of the day, and the number of arrivals on the runway in the last 20 minutes also seemed to be of importance. The UDP categorical describes if the landing occurred during the daylight period at AAS or not. Landings outside of UDP tend to have slightly longer ROT on average, probably due to the reduced visibility. Same reasoning applies to the visibility (zicht) feature, however low visibility operations were scarce in the dataset which could cause the model to not use this as feature as much during modelling. Figure 54 shows the distribution of the ROT for the different UDP categories.

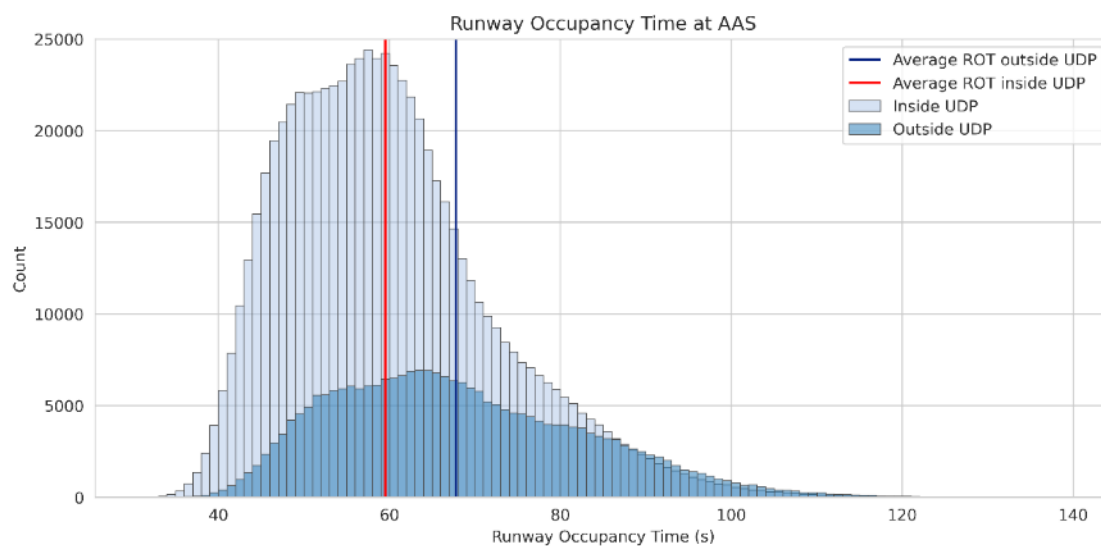


Figure 55: Distribution of the ROT for different UDP categories.

Lastly airport throughput related features such as d20m and d20m_rw were indicated to be important. This is an expected observation as aircraft tend to get instructed to expedite vacating of the runway during peak hours of traffic. By doing so, a higher traffic throughput can be achieved.

E.6.1.4 ROT – with runway exit

The second scenario of the ROT machine learning prediction model did consider the runway exit that would be used in the feature set. The feature importance plot can be seen in Figure 55.

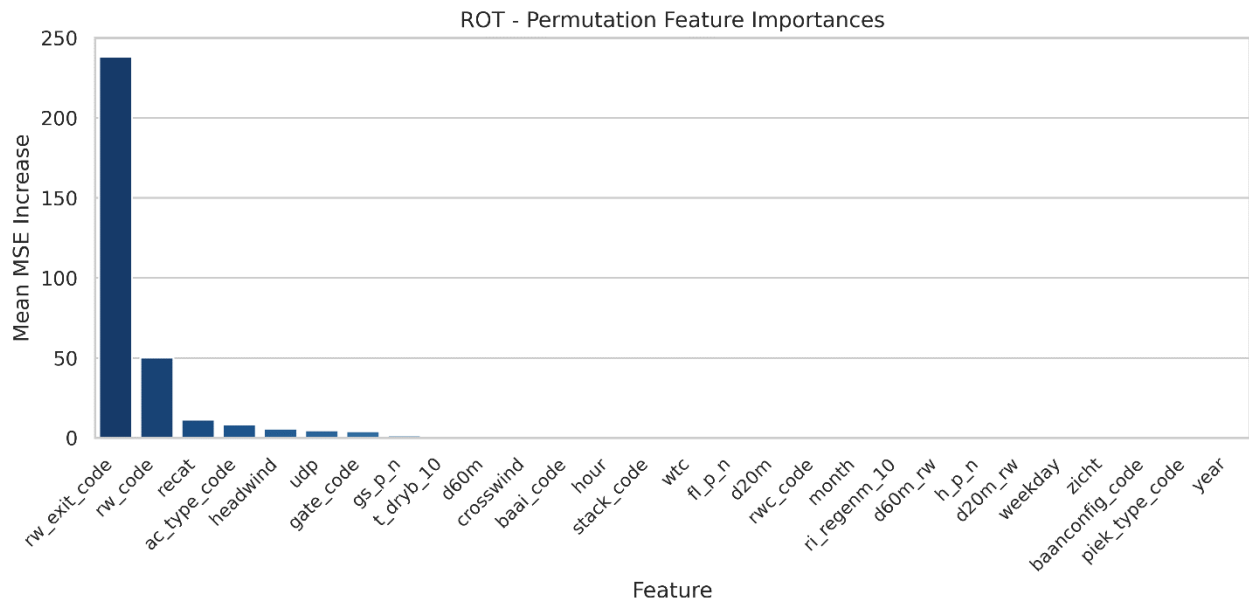


Figure 56: Feature importance of the ROT prediction model where the runway exit was not included in the feature set.

As expected, the runway exit was calculated to be, by far, the most important feature. Since runway exits codes are unique for the entire airport, the runway exit also incorporated the runway into the exit code. However, it did not incorporate runway ends into the feature, as a landing on either runway end could potentially result in a runway exit at a specific location.

Another factor worth noting is the different ranking of the features in this scenario. Instead of the feature ranking in terms of performance being the same as in the previous scenario, this scenario shows a different feature importance ranking for some features. One of those features is the headwind, which was calculated as the 12th most important feature in the previous scenario. However, in this scenario the headwind is considered the 5th most important feature.

Reasoning for the changed ranking is probably due to the fact that the model's training is completely different than in the previous scenario, since this scenario includes such an important feature (runway exit code).

Other features that are considered important were also mentioned in the previous scenario. Reasoning for these feature importance's are described there.

E.6.2 One vs many models

It is common practice to train a single model for a complete training set. Because the ROT is highly dependent on the layout of the different runways, the training of separate models for the different runways was evaluated. When separate models are trained for the different runways, the dataset is

split up per runway and the runway feature is dropped. This was done for both the feature sets with and without the runway exit.

Table 32 shows the validation set MSE for rot prediction models trained with a label encoded feature set both with and without the runway exit. In the case a single model was trained, the validation set was split up per runway and the validation error was calculated. When multiple models were trained the MSE across all runways was calculated by taking a weighted average of the validation set predictions of each model.

In the case that the runway exit was present in the features the overall MSE was 0.01 s^2 smaller when a single model is trained as opposed to multiple models. Conversely, when the runway exit feature was omitted training multiple models resulted in an increase in performance of 0.1 s^2 MSE. Because the performance gain by training multiple models was marginal, and training a single model is the simpler solution, it was decided to train a single model for all runways.

runway	single model, with exit	multiple models, with exit	single model, without exit	multiple models, without exit
18R	27.57	27.67	111.91	111.77
18C	27.97	28.03	85.72	85.53
06	32.02	31.94	109.11	108.87
36R	24.11	24.25	69.20	69.47
22	49.51	48.41	74.14	72.93
27	30.12	30.07	65.30	65.57
36C	20.96	20.78	31.53	31.51
all runways	28.37	28.38	92.17	92.07

Table 32: Validation set MSE for rot prediction models with 1000 estimators and a minimum of 5 samples per leaf. Single model indicates that one model was trained for all runways. Multiple models means a different model was trained for each runway. The all runways MSE shows the weighed (by number of flights) average of the MSE per runway.

E.6.3 Best Models

E.6.3.1 TTF

Table 33 shows the performance of the TTF prediction models. Two different baseline models were developed. In the first baseline model the mean TTF per runway was taken as the prediction value. This resulted in an MSE of 84.1 s^2 on the test set. For the second baseline the mean TTF per runway and aircraft type was taken as the predicted value. This resulted in a significantly lower MSE of 55.3 s^2 .

For the TTF models the hyperparameters that were found to be optimal were a number of estimators of 1500, a maximal samples per leaf of 2, and the max features hyperparameter was set equal to the total number of features. Models were trained with the optimal hyperparameters for both feature sets. In both feature sets, the final test score MSE was 15.7 s².

Model	feature set	encoding	train MSE (s ²)	test MSE (s ²)
baseline runway	-	-	80.7	84.1
baseline runway, aircraft type	-	-	51.6	55.3
random forest	without 5 NM	label	2.6	15.7
random forest	with 5 NM	label	2.7	15.7

Table 33: Best models for TTF prediction. The best performing hyperparameters across all feature set encodings were 1500 estimators and a maximal samples per leaf of 2.

Figure 56 shows the distribution of the error, or the actual TTF minus the prediction, of the model predictions for both feature sets. The baseline plots in this figure refer to the optimal baseline, where the average TTF per runway and aircraft type is taken. It can be seen that the distributions of the errors resulting from the random forest predictions are significantly narrower than that of the baseline, thereby indicating the models offer a significant improvement over the baseline. The distribution of the errors is very similar for the different feature sets. It can be seen that the error distributions are slightly skewed.

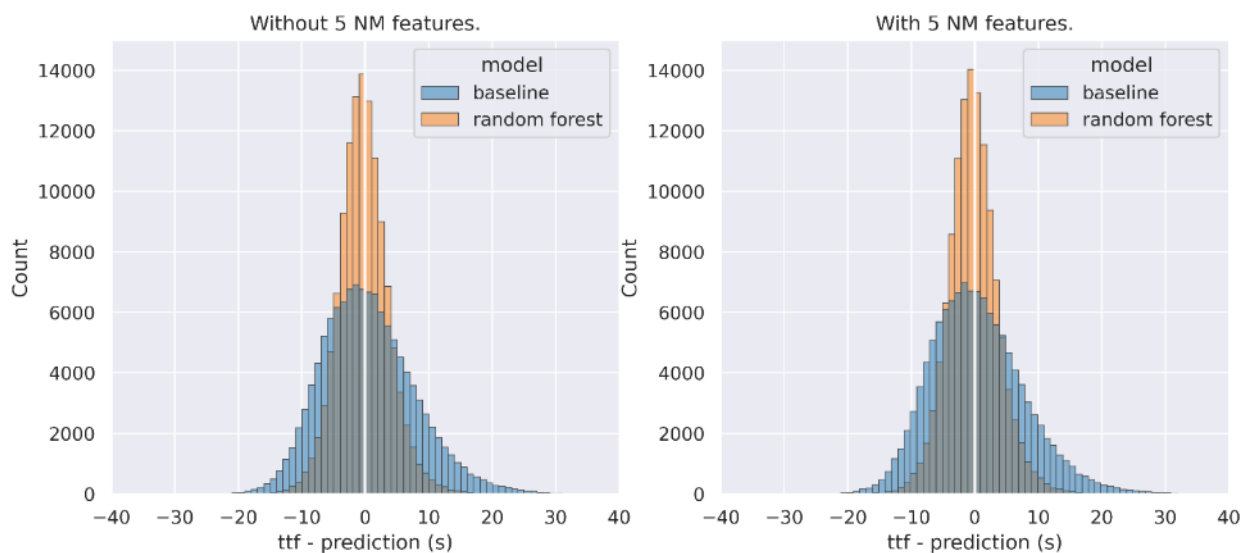


Figure 57: Plots of the distribution of the errors of the TTF prediction models. The error distribution was plotted for both feature sets, i.e. with and without 5 NM features. For the baseline models the mean TTF per runway

and aircraft was taken as the prediction value. The random forest models were trained with the hyperparameters of 1500 estimators and a minimal samples per leaf of 2.

E.6.3.2 ROT

Table 34 shows the performance of the ROT prediction models on the test set for both the feature sets with and without the runway exit feature. Two different baselines were developed. In the first baseline the mean rot per runway and aircraft type is taken as the prediction. The second baseline takes the mean ROT per runway exit as the prediction. The baseline models achieve an MSE of 111.9 s² and 47.4 s² respectively on the test set.

The random forest models were trained with the optimal hyperparameters, which were found to be 1000 estimators and a minimal samples per leaf of 5. When the runway exit was not included as a feature the test MSE was found to be 93.2 s². In the case the runway exit was included as a feature the test set MSE was found to be 28.1 s². It can be seen that the baseline where the mean per runway exit is taken as prediction exceeds the performance of the random forest model where the runway exit is not included in the features.

Model	feature set	encoding	train MSE (s ²)	test MSE (s ²)
baseline runway, aircraft type	without runway exit	-	113.6	111.9
random forest	without runway exit	label	38.4	93.2
baseline runway exit	with runway exit	-	48.3	47.4
random forest	with runway exit	label	12.1	28.1

Table 34: Best models for ROT prediction. The random forest models were trained with the optimal hyperparameters of 1000 trees and a minimal number of samples per leaf of 5.

Figure 57 shows the error distribution of the ROT prediction models. It can be seen that the improvement of the random forest models over the baseline models is smaller in the ROT prediction than in the TTF prediction models. Both error distributions are skewed.

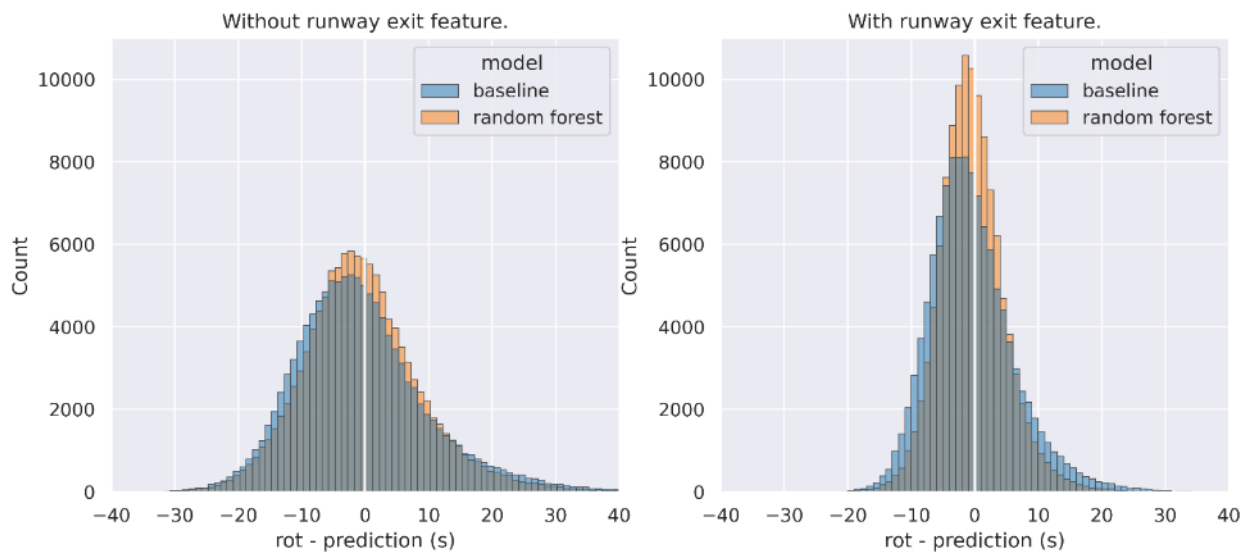


Figure 58: Plots of the distribution of the ROT errors. In the left figure the distribution of the errors of the predictions of the baseline where the mean of the ROT per runway and aircraft type is taken as the prediction, and the random forest model where the runway exit feature is not included. The right plot shows the error distribution of the baseline where the average ROT per runway exit is taken and the random forest model where the runway exit feature is included. Models were trained with the optimal hyperparameters of 1000 estimators and a minimal number of samples per leaf of 5.

Other, more detailed results, per Schiphol runway, and per aircraft type, have been made confidential for strategic purposes.

E.7 Conclusions and Recommendations

E.7.1 Conclusions

The TTF machine learning prediction models offer a considerable improvement over the baseline method for predicting the TTF. The improvement in MSE is almost 40 s^2 . The TTF baseline is based on the average TTF per runway per aircraft type. The test set MSE of the best TTF model was found to be 15.7 s^2 . For the TTF prediction model, the feature importance calculation indicated that adding features containing information about the state of the aircraft at the 5 NM point did not significantly improve the model's predictions. The current model uses the 4 NM to threshold as the inference point. Changing this inference point to different points along the approach path might offer an improvement in the model performance when including the information of a previous point.

In the case of the ROT prediction, even though the random forest models outperformed the baseline models, the performance gain by using machine learning models over the baseline models was much smaller than in the TTF case. The reduction in MSE compared to the baseline was found to be approximately 20 s^2 for both when the runway exit was included as a feature and when it was not. Moreover, it was found that the baseline model when the runway exit was included outperformed the best random forest model when the runway exit was not included as a feature. This emphasizes the importance of knowing the runway exit that will be used when predicting the ROT. Machine learning

model predictions of the ROT without the runway exit in the feature set are not considered good enough to be used in practice by, for example, an ATCO.

Both the TTF and ROT were modelled for AAS, based on data of operations at AAS. It is possible to apply the method as described in this report on other airports as well. However, it would be required to obtain similar datasets from those airports, especially for modelling the ROT. As ROT is greatly dependent on airport infrastructure and applicable runway exiting procedures, modelling ROT based on data from another airport would be expected to lead to an unacceptable degradation in performance. If a model trained on data from AAS were to be used to make predictions on data from another airport it would be required to reassess the performance. Lastly, the model's performance as described in this report is dependent on the input dataset, algorithm and model parameters that were used. Training the model on data from other airports may give different performance results.

E.7.2 Recommendations

A number of features that were mentioned in chapter E.2 were not present in the dataset and if added could increase the performance of the models. One of those features is the aircraft operator. Aircraft operators usually have SOP's (Standard Operating Procedures) that describe how a final approach and landing should be performed. By using the aircraft operator as an input feature to the model approach and landing characteristics resulting from operator dependent SOP's might be included in the dataset.

Another possibly important missing feature was the separation between the aircraft for which the TTF and ROT were predicted and the following flight. The distance to the following aircraft can influence the speed profile of an airplane. When an aircraft pair is separated close to the separation minimum the leading aircraft might be instructed to fly at a higher speed to prevent under separation. Furthermore, it would be advised to investigate whether the TTF prediction models could be further enhanced if the dataset would incorporate aircraft mass (weight), IAS and TAS. However especially aircraft mass is a very much desired but not yet widespread available data element.

In order to improve the ROT predictions, adding information to the data that indicates which runway exit is likely to be used could increase the model performance. The runway exit was found to be the most important feature in the ROT prediction. Therefore, adding features that can provide the model with information about which exit is going to be used would be the most obvious way to improve the model. One possible approach would be to train a classifier model that predicts which exit is most likely to be used, or that outputs a probability distribution over all the runway exits. The predicted runway exit or distribution of runway exits could then be provided as features to the ROT regression model, which might lead to an improvement in the prediction accuracy.

This study focused on the use of random forest algorithms. Although the random forests often achieve high performance on tabular datasets, more modern approaches such as neural networks might be better able to extract complex patterns from the data. An example of a complex pattern that might be present in the data could for example refer to the dynamics of the airplane from the successive measurements. In addition, the dataset used in this study is relatively large which would benefit complex models such as neural networks. Next to that, alternative decision tree methods such as gradient boosting trees have been shown to offer improved performance on a number of datasets. Therefore, it is recommended to explore alternative algorithms.

If TTF and ROT predictions were to be integrated in ATM products or tools, having uncertainty estimates of the predictions could be important to the usefulness and acceptance of such applications. One straight-forward way of estimating the uncertainty in predictions of a random forest is by making use of bagging [E.6]. In general, random forests make use of bagging when making predictions by averaging over the predictions of the decision trees that make up the random forest. In a similar way the variance of the predictions of the decision trees can be calculated, which can indicate the uncertainty of the predictions.

A second method for determining the uncertainty is by using a quantile regression forest model. Quantile regression forests have been used before in TTF prediction studies [E.8]. Quantile regression forests are an extension of random forest models where the quantile function is constructed from the predictions of the decision tree estimators that make up the forest.

Finally, improving further and incorporating TTF and ROT predictions in the ATC operations will require a thorough understanding of the current procedures and extensive cooperation with the intended users of the tools. New operational procedures such as RECAT-EU will influence the requirements on the TTF and ROT. Understanding the challenges of new procedures can guide the development of tools. Therefore it would be useful to think about how TTF and ROT predictions can be further improved and operationally used in the ATC system in practice and how they can be integrated in support tools for the ATCOs.

E.7.3 Acknowledgements

LVNL is kindly thanked for providing the dataset for this study.

E.8 Baseline ROT models

The baseline models, for which the results are available at NLR, are based on the mean of the ROT per runway and aircraft type. In a similar way the mean ROT per runway, mean ROT per runway and RECAT category and mean ROT per runway and aircraft type were calculated across the full processed dataset, consisting of the train, validation and test set. However these numerical results are made confidential to this report.

E.9 References used in Appendix E

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Appendix F WP2/WP4 Identification of Inconsistent Aircraft Type and Registration in Flight Plans

F.1 Introduction

Another aspect that came out of the WP2/WP4 workshops held is that there might be a reason to have a safety requirement for validating the “aircraft type” when this is used as a data input source in a system that derives aircraft spacing based on Pair-Wise Separation, meaning based on the RECAT-EU-PWS tables. As such a dedicated exploration study was done to check on a sample set if this could really become a safety aspect requiring a safety-mitigation. This Appendix reports on the sample study executed by NLR that reveals that indeed a dedicated risk-mitigation activity seems to be needed.

With the introduction of time-based separation (TBS), pairwise wake turbulence separation (PWS) and reduced minimum radar separation (MRS), the separation minima between aircraft are reduced. Where TBS converts a distance-based separation (DBS) to a time equivalent, pairwise separation and reduced MRS reduce the required DBS between aircraft. Pairwise separation computes a required separation minima per aircraft type pair. As the separation minima between an aircraft pair relies on the aircraft type, it becomes increasingly important that the aircraft type is correctly transmitted to the air traffic controller (ATCO) via the aircrafts Mode-S. An incorrect aircraft type being transmitted, can lead to incorrect aircraft spacing which can lead to an under-separation and/or a wake turbulence encounter.

The purpose of this Appendix is to describe the analysis of Air Traffic Service (ATS) data, which goal is to find inconsistencies between transmitted ICAO Mode-S addresses and the aircraft type and the aircraft registration compared to the aircraft type and registration as recorded in external databases.

This Appendix is structured as follows. After this first introduction in Chapter F.1, the datasets used in the analysis are described in chapter F.2. Then, in Chapter F.3 the method for identifying inconsistencies in the data is described. Thereafter, the results are described in Chapter F.4 followed by Chapter F.5 that concludes the analysis. Finally, Chapter F.5 provided the used bibliography.

F.2 Data

This chapter describes the different datasets used in this research. Each dataset is described in a separate section in this chapter.

F.2.1 ATS data

The ATS data used in this research consists of 1 year of ARTAS data from the LVNL, the Dutch Air Navigation Service Provider (ANSP). The data is retrieved with help of the NLR FANOMOS application program interface (API). The data consists of all the flights of the months November and December 2021 that were arriving or departing at Amsterdam Airport Schiphol. The flights are pre-processed by

removing flights without a flight plan, aircraft registration or Mode-S address. After pre-processing, 61,145 flights remain in the dataset.

For each flight, the following information is available:

Start Datetime	The UTC date and time of when the flight was first tracked by the ARTAS Tracker.
Aircraft Registration	The aircraft registration
ICAO Mode S Address	The transmitted ICAO 24 bit Mode-S address.
ICAO Aircraft Type	The ICAO aircraft type code

F.2.2 ILT Aircraft Register

The ILT Aircraft Register is a public data source from the Dutch CAA. This register contains the Mode-S address of all civil aircraft that have a Dutch registration and transponder. The register was downloaded as an Excel file from the ILT website. In the register the aircraft registration, aircraft type and Mode-S address per aircraft is available. In total, the register contains 2,910 rows of data.

F.2.3 ADS-B Equipment Vendor Database

The last data source used for the analysis is a database that can be downloaded from the webpage of an ADS-B equipment vendor. This dataset contains worldwide Mode-S addresses, aircraft registrations and aircraft types of civil aircraft. In total, the database contains 190,970 entries.

F.3 Methodology

This chapter describes the methodology for comparing Mode-S addresses with the filed aircraft type and aircraft registration. For both comparisons, the Mode-S address shall function as the key value. Each comparison will be done with two datasets.

The starting point of each comparison, is the ATS dataset containing 61,145 flights that arrived and departed Schiphol in the months November and December 2021. For each flight, the aircraft type and aircraft registration is included in this dataset and originates from the flight plan that was filed to the ANSP. Next, for each flight, aircraft type and aircraft registration data is joined on the ATS dataset from one of the following sources:

1. The ILT Aircraft Register

2. ADS-B Equipment Vendor

After joining these data sources on the complete ATS dataset the following metrics will be derived from the resulting data:

1. Number of times an aircraft type inconsistency was recorded:
 - a. Compared to the aircraft type in the ILT Register;
 - b. Compared to the aircraft type in the ADS-B register
2. Number of times an aircraft registration inconsistency was recorded:
 - a. Compared to the aircraft registration in the ILT Register;
 - b. Compared to the aircraft registration in the ADS-B register

F.4 Results

F.4.1 Data Joining

ILT Register Join

In total, 36,529 flights were joined with the data in the ILT Register, resulting in 59.7%. This low percentage of joined flights is primarily caused by the limited scope of the ILT Register, as this register only contains records of aircraft with a Dutch registration. Most flights that could not be joined were operated by foreign registered aircraft.

ADS-B Register Join

In total, 60,525 flights of the ATS dataset were joined with the ADS-B Register, this results in a total of 98.9% of all flights within the ATS sample. As this register contains a worldwide aircraft register, also registration and type data of foreign aircraft could be joined to the ATS sample.

F.4.2 Aircraft Type Checking Results

The following two sections describe the number of occurrences where an inconsistency in the aircraft type was found.

Aircraft Type check with the ILT Register

25 occurrences, hence 0.068 %, where the aircraft type that was included in the flight plan was different than the aircraft type that corresponded with the aircraft type in the ILT Register. Most

inconsistencies involved Embraer aircraft where the Embraer E35L was filed in the flight plan, but the ILT Register reported the E135. The difference between the E35L and the E135 seems minor in terms of aircraft dimensions, but the E35L seems to be an business jet version of the E135. Other inconsistencies featured other Embraer aircraft, the Boeing B737-7 and B737-8 aircraft and the Airbus A310 and Airbus A330

Aircraft Type check with the ADS-B Equipment Vendor Database

Checking for inconsistencies against the ADS-B Register resulted in 359 inconsistencies in total, hence 0.59 %. Most inconsistencies involved small aircraft such as private jets. For example 190 inconsistencies were found with Dassault aircraft. In some of these cases the F900 vs the F9EX were reported, differences between these two types seem to be mostly generational, for example the F9EX is reported to be a F900 but with improved range, engines and a glass cockpit. Inconsistencies featuring heavier commercial aircraft were found as well, such as 6 inconsistencies with Airbus aircraft, 5 with Embraer aircraft and 1 with a Boeing aircraft.

F.4.3 Aircraft Registration Checking Results

This section describes the number of occurrences where the filed aircraft registration was different from the aircraft registration that was reported in the ILT Register and the ADS-B register.

Aircraft Registration check with the ILT Register

Only 2 occurrences, hence 0.005 % of the sample population, were found where the aircraft registration of the filed flight was different than the registration known by the ILT to correspond to the Mode-S address. However, whilst the aircraft registration was inconsistent across these two sources, the aircraft type was consistent.

Aircraft Registration check with the ADS-B Equipment Vendor Database

When checking the aircraft registration for inconsistencies, 177 occurrences were found, a 0.29% of the sample population. Of the 177 occurrences, most of these involved civil commercial aircraft. For example, 99 occurrences involved Airbus aircraft, 48 aircraft involved Boeing aircraft and 13 occurrences involved Embraer aircraft.

F.5 Conclusions

This study has compared the aircraft registration and aircraft type of flight plans to publicly accessible sources to determine whether inconsistencies occurred between the filed aircraft registration and type and the corresponding aircraft registration and type in the public source. The data sources were joined on the ICAO 24-bit Mode-S address. The publicly available data sources that were used in this

comparison, are the Dutch CAA ILT aircraft register and a publicly available ADS-B equipment vendor database. These two sources contain information of individual airframes, including its corresponding aircraft type and ICAO 24-bit Mode-S address. The flight plan data originated from the FANOMOS Flight Data Service of the NLR.

General Conclusions

The analysis showed that inconsistencies between the flight plans and the public sources exist. However, with the limited information available it is not possible to indicate if the inconsistency is an error on either side of the two data sources.

Also, concerning the comparison between the filed aircraft type and the type that was recorded in the public source, some of the aircraft types that were recorded in the public source, did not exist in the official ICAO Type Designation manual [F.1]. For example, inconsistencies with Dassault Falcon 900 aircraft were found where the flight plan reported an F900 aircraft type and the ADS-B Register recorded an F9EX aircraft type. However, the F9EX is not included in Doc. 8643 as an official type designator. This indicates that the comparison is made with sources which both have their own limits and caveats.

Hence the overall conclusion is that the inconsistencies observed, especially when seen in the context of future air traffic control pair-wise separation systems, where aircraft type forms a real important system input parameter to determine the actual wake separation (time or distance), deserve dedicated risk-mitigation attention. Especially when applying aircraft type inside such a future air traffic control system, ways should be found to detect and flag to the air traffic controller any of such inconsistency occurrences, when these would occur in real life operation.

Aircraft Type Inconsistencies

The comparison indicated that there were occurrences where the aircraft type in the flight plan did not match with the aircraft type in the ILT and ADS-B register. Comparisons with the ILT Register reported 25 occurrences, in particular inconsistencies with aircraft from Embraer. Where the comparison with the ADS-B register reported 359 inconsistencies, of which primarily involved smaller and lighter aircraft, commonly used as a private jet. However, as described in the general conclusions section above, some of these inconsistencies involved reported aircraft types that were not included in ICAO Doc 8643 [F.1].

Aircraft Registration Inconsistencies

In total, only 2 occurrences were found where the registration that was included in the flight plan differed from the registration in the ILT Register. When comparing the flight plan aircraft type to the ILT Register 24 inconsistencies were found. When checking the aircraft registration for inconsistencies with respect to the ADS-B Register, 177 occurrences were found, versus 359 occurrences when checking for aircraft type inconsistencies.

The difference in number of inconsistency occurrences between aircraft type and aircraft registration suggest that it is more common to find an inconsistency in aircraft type than with aircraft registration. This is noticeable as an aircraft registration is a unique identification of an individual airframe, where the aircraft type is a type designator that can be the same for multiple airframes in an air operators fleet. Hence it could be more obvious to see more inconsistencies with regard to aircraft registrations as there are as much variations for this designation as there are aircraft in the fleet of an operator. A possible explanation for the increased probability of having inconsistent aircraft types is that when a last minute aircraft change occurs at the operator, the registration in the flight plan is adjusted to include the replacing aircraft, however the aircraft type was not adjusted as well.

F.6 Bibliography

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