



Final Report of NEFAT (Noise Exposure in Future Air Traffic)

Authors:

Xin Zhao *(Chalmers)*

Evangelia Maria Thoma *(Chalmers)*

Project partners:

Peter Lukic *(Swedavia)*

Olivier Petit *(LFV)*

Ulf Tengzelius *(Aurskall akustik)*

Document History:

<i>Version</i>	<i>Effective Date</i>	<i>Page(s) Affected</i>	<i>Extend of Change</i>
1.0	2025-05-15	All	

--	--	--	--

Nomenclature

Abbreviation	Explanation
AEDT	Aviation Environmental Design Tool
AIP	Aeronautical Information Publication
APCH	Approach
EPNL	Effective Perceived Noise Level
ESGG	Göteborg Landvetter airport ICAO identifier
ESSA	Stockholm Arlanda airport ICAO identifier
FAA	Federal Aviation Authority
GHSL	Global Human Settlement Layer
IAC	Instrument Arrival Chart
IAF	Initial Approach Fix
ICAO	International Civil Aviation Organization
Kt	Knots
Lamax	Maximum A-weighted Sound Pressure Level
Lden	Day-evening-night noise level
NM	Nautical Miles
RF	Constant Radius arc to a Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RNP AR	RNP Authorisation Required
RWY	Runway
SEL	Sound Exposure Level
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival

Contents

Nomenclature	3
Executive Summary	7
1 Introduction	8
1.1 Background	8
1.2 Project objectives and achievements	8
1.3 Report structure	9
2 Methodology	10
2.1 Aircraft noise prediction methods and tools	10
2.2 Meteorological data	10
2.3 Population data	10
2.4 Future aircraft concept considered	11
2.5 Noise metrics	11
2.6 Multidisciplinary analysis framework	12
3 Results and discussions	13
3.1 Noise-optimal RNP AR approach procedure	13
3.1.1 Optimization result of ESSA RNP _y AR RWY01R procedure	13
3.1.2 Parametric study of other ESSA RNP AR approach procedures	16
3.2 Noise-optimal RNP AR approach procedure with wind conditions	22
3.2.1 Noise from Flight Procedure Designed with Statistical Wind: Auralization and Psychoacoustic Evaluation	22
3.2.2 Analysis of noise optimal approach procedures with on-site statistical meteorological effects	26
3.3 Noise mapping for the future aircraft fleet	30
3.3.1 Aircraft fleet modelling with hybrid/electric aircraft	30
3.3.2 Impact of future aircraft concepts on noise mapping from aircraft fleet operation	31
3.4 Validation	33
4 Conclusions and recommendations	36
5 Communication and dissemination	37
6 Reference	38

List of figures

Figure 1 Illustration of noise assessment procedure within Chalmers Framework for Aircraft Multidisciplinary OptimizationS (FAMOS)	12
Figure 2 ESSA RNP y RWY 01R (AR) procedure: original from LFV (Top) and reproduced for optimization (Bottom)	14
Figure 3 Noise affected population relative to turn radius variation for RNP y RWY 01R (AR) (Left) and the affected population distribution above SEL 65dB(A) from highlighted procedures (Right)	15
Figure 4 ESSA RNPz RWY 01R AR/RNPw RWY01R AR procedure: original procedure from LFV (Top) and turning radius variation results (Bottom)	16
Figure 5 ESSA RNP _y RWY01L AR/RNP _x RWY01R AR procedure: original from LFV (Top) and turning radius variation results for RNP _y RWY01L AR (Bottom)	17
Figure 6 ESSA RNP _x RWY19R AR procedure: original from LFV (Top) and turning radius variation results (Bottom)	18
Figure 7 ESSA RNP _y RWY19R AR procedure: original from LFV (Left) and turning radius variation results (Right)	19
Figure 8 ESSA RNP _y RWY26 AR procedure: original from LFV (Top) and turning radius variation results (Bottom)	21
Figure 9 RNP AR approach procedure designed based on statistical wind (Left) and comparison with existing RNAV STAR RWY 03 Closed approach procedure (Right)	22
Figure 10 Approach procedure design example- RNP AR ESGG RWY 03: with statistical wind (black solid line); with ICAO standard wind (red solid line).....	23
Figure 11 A zoom-in of the RNP AR procedure designed design example- RNP AR ESGG RWY 03: with statistical wind (green solid line); with ICAO standard wind (red solid line).....	23
Figure 12 SEL contour lines and population exposed to noise level higher than 70 dB(A) depicted as dots for the standard (red) and test procedure (black).....	24
Figure 13 Spectrograms of the synthesized approach noise at the three selected observer points as given in Figure 12.....	25
Figure 14 Sound quality metrics for the three selected points and two procedures considered.	27
Figure 15 SEL contours for the existing and optimal procedures from Section 3.1.1 with weather conditions.....	28
Figure 16 Hybrid/electric aircraft model retrofitted from Dornier 328	30
Figure 17 Lden contours for the four scenarios as defined in Table 11	32
Figure 18 Comparison of ESSA RNP _y RWY01R AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right).....	33
Figure 19 Comparison of ESSA RNP _y RWY19R AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right).....	33
Figure 20 Comparison of ESSA RNP _y RWY26 AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right).....	34
Figure 21 Comparison of ESSA RNP _y RWY26 AR single event noise mapping of ATR72 from ECACdoc29 method (left) and FAMOS/CHOICE (right).....	34
Figure 22 Comparison between the synthesized noise computed from CHOICE and measured noise from ANT project	35
Figure 23 Comparison of Lden contour of 2024 scenario case from ECACdoc29 method (left) and FAMOS/CHOICE (right).....	35

List of tables

Table 1 Existing RNP AR procedures used for optimization	13
Table 2 Fuel burn, NOx emissions and noise impact for the original existing and optimized ESSA RNP y RWY 01R (AR)	15
Table 3 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPz RWY 01R AR/RNPw RWY01R AR procedures with RF turning radius variation	17
Table 4 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPz AR RWY01L procedure with RF turning radius variation.....	18
Table 5 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPx AR RWY19R procedure with RF turning radius variation.....	19
Table 6 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPx AR RWY19R procedure with RF turning radius variation.....	20
Table 7 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPz RWY26 AR procedure with RF turning radius variation.....	20
Table 8 Fuel burn, NOx emissions, and noise impact for the ESSA RNPz RWY26 AR procedure with RF turning radius variation.....	24
Table 9 Fuel burn, NOx emissions, and noise impact for the ESSA RNPz RWY01R (AR) procedures with statistical weather conditions and ISA conditions.....	29
Table 10 Hybrid/electric aircraft model parameters	30
Table 11 Air traffic and fleet model data used for aircraft fleet noise assessment at Arlanda airport	31

Executive Summary

This is the conclusion report of “Noise Exposure in Future Air Traffic” (NEFAT) which is a project funded by the Swedish transport administration Trafikverket through the framework of the Center for Sustainable Aviation (CSA). Building on the competence of aircraft noise assessment, high precision navigation procedure design and meteorological database from ANT, CIDER, SAFT and STATMET, which are projects funded by Trafikverket within the framework of CSA, the 2-year project NEFAT targets the interdependencies of future air traffic by high precision navigation, noise emissions as well as more environment friendly aircraft.

Through the optimization and parametric study of existing Required Navigation Performance Authorization Required Approach (RNP AR APCH) procedures at Stockholm Arlanda (ESSA) airport, the results show that the existing procedures at ESSA are well designed in balancing emissions, noise, fuel consumption under current practical constraints and regulations. Improvements can be made to the existing procedures weighing noise impact. However, most of the improvements would require the revision of the radius to fix (RF) turning radius through reducing ground speed or/and increasing aircraft bank angle capability. One practical possibility is to apply local statistical wind data, which is lower than ICAO standard tailwind components for ESSA, in procedure design. On the other hand, the analysis of the noise optimal approach procedures with on-site statistical meteorological effects shows that realistic wind conditions could significantly affect the optimization results with standard wind conditions. In the example of ESSA RNP RWY01R (AR), the selected historical statistical weather conditions were unfavorable for the noise generation and propagation due to the higher atmospheric temperature and the wind direction which resulted in a higher power requirement.

By incorporating statistical meteorological data in procedure design, the noise impact of an RNP AR APCH procedure at Göteborg Landvetter (ESGG) airport has been quantified and compared to that of a similar procedure designed with the ICAO standard tailwind component. From the psychoacoustic evaluation of the noise exposure of three representative locations along the flight path, the average annoyance levels do not change because of the change in the procedure’s lateral path. But, as the lateral path of the procedure is shifted away from densely populated areas, less people are affected by the arrival operation through the procedure designed with statistical wind compared to the procedure designed with standard ICAO tailwind.

With the establishment of a future aircraft fleet consisting of hybrid/electric aircraft, the noise footprint of such a fleet for ESSA airport has been assessed. The result is however depressing as the introduction of electric aircraft will lead to more frequent departures and landings because of much smaller passenger capacities, hence higher noise impact with larger affected areas considering day-evening-night equivalent noise level. The outcome may vary if, in the future, spatially distributed small airports are utilized instead of the large, centralized airports used today.

1 Introduction

1.1 Background

After the hit of COVID-19, global air traffic is now moving back to a recovery and growth path. Albeit, the growth will be slower than earlier forecasted, future air traffic still needs to meet its challenge in achieving the environmental goals. Talking about future air traffic management, two major features, high precision aircraft navigation and more environmentally friendly aircraft have to be discussed.

For the former, one could easily name several environmental benefits brought by high precision navigation flight, such as reducing flight times, cutting fuel consumption and emissions and increasing traffic capacity. In a previous feasibility study done by the project partner LFV and Novair (IRIS-programmet) (Ekstrand et al., 2022), noise emissions related to non-straight approaches with variable approach angles have been explored within the framework of IRIS program in 2021-2022. The result suggests that it is possible to influence the noise levels on the ground through re-constructing the approach procedures. The RNP AR APCH (Required Navigation Performance Authorization Required Approach) procedures can, by allowing the aircraft to make turns near the runway, avoid urban areas approaching the airport.

Whilst for the latter, the more environmentally friendly aircraft such as electric or hydrogen powered aircraft may have the potential of removing most inflight emissions. On the other hand, the impact on noise emissions from adopting these technologies is not clear. Furthermore, weather conditions could play an important role in noise propagation, operational behaviour and procedures selection as the global climate condition has been changing faster. With the data demonstrator established in project STATMET (TRV 2019/60993), statistical historical meteorological data around the area of Stockholm Arlanda and Gothenburg Landvetter airports can be applied to the investigation of the impact of realistic weather data on the noise optimal procedures.

1.2 Project objectives and achievements

This project has concentrated on realizing the noise reduction benefits of the two features (high precision navigation + environmentally friendly aircraft) in several real-world air traffic management scenarios, with and without the consideration of historical statistical weather conditions. The objectives of the project have been focusing on two aspects:

- Reduce noise exposure to the communities near the airport through applying high precision aircraft navigation and future gas turbine free aircraft concepts.
- Investigate the impact of real wind conditions on the aircraft operational behavior and associated noise propagation.

Taking the two major airports within Sweden, Arlanda and Landvetter as the study objects, the objectives have been achieved through four studies as listed below. In addition to the focus of noise, fuel consumption and gaseous emissions have been calculated along with the studies of noise assessments.

- the first study has been optimizing the existing RNP AR APCH procedures for minimal noise exposure to the communities around the Arlanda airport, without the consideration of wind conditions.
- the second study has been quantifying the benefits in terms of fuel savings, emissions and noise reductions from applying statistical meteorological data into an RNP AR APCH procedure design practice for the Landvetter airport done in STATMET.

- the third study has been applying realistic weather conditions to the noise assessment of the noise optimal procedures derived from the first study.
- in the last study, the noise footprint at Arlanda airport from a future aircraft fleet has been evaluated against the noise footprint from the modelled existing modern aircraft fleet.

1.3 Report structure

This report, as the final deliverable reporting the methods used in the project and outcomes generated from the work in detail, is divided into the following sections:

- In the first section “Introduction”, a general introduction of the project background is presented as well as the structure of the report and the key objectives and achievements of the project.
- In the second section “Methodology”, key information about the methods used and developed for noise assessment, the data source of the historical meteorological data, population distribution data, the future aircraft concept down selection and the noise metrics presented in the report are described.
- In the third section “Results and discussions”, the results produced from the conducted studies are given. The first part is the optimization and parametric studies of the RNP AR procedures at Arlanda airport; the second part includes two studies, one is the noise assessment of an RNP AR procedure designed from statistical wind condition at Landvetter airport while the other is applying statistical wind condition to the noise assessment of one optimized RNP AR procedure at Arlanda airport; the third part presents the noise impact from future aircraft fleet and the section ends with validation of the presented results with an authority recommended tool.
- Conclusions and future work recommendations are listed in section four while communications and disseminations are reported in section five.

2 Methodology

2.1 Aircraft noise prediction methods and tools

To perform the assessment of noise from aircraft operations, two methods can be applied. The first one which has been widely used are the ECACdoc29 (ECAC.CEAC Doc 29, 2016) and the Federal Aviation Authority's (FAA) Aviation Environmental Design Tool (AEDT) (Aviation Environmental Design Tool (AEDT) Version 3d, 2021), which predicts the noise level according to ECACdoc29 or ICAOdoc9911(Recommended Method for Computing Noise Contours Around Airports, Doc 9911, 2nd Edition, 2018). These tools are based on what is commonly referred as integrated methods, which use databases and consider the aircraft as a whole. They provide a good prediction for long-term averages, but do not provide any information about the contribution of the individual noise components and rely on the database of existing aircraft. In addition, a recent study reporting a validation case of the ECACdoc29 (Lautsch et al., 2024) has shown that even though a strong correlation between ECACdoc29 predictions and measurements is observed, the calculations are however tend to underestimate the noise levels, particularly for arrival cases. Nevertheless, as ECACdoc29 is the method developed and used by the authorities, it has been adopted as the validation basis for the results generated from the project. The originally planned validation using Airbus Performance Engineer's Programs (PEP) has been cancelled because the partner Novair was shut down and quit the project unfortunately.

Another type of aircraft noise prediction, that can help in understanding the noise source breakdown and predicting the noise from non-existing aircraft concept, is based on empirical and semi-empirical correlations. CHalmers nOlse CodE (CHOICE), an aircraft noise prediction tool based on empirical and semi-empirical models available in public literature, with the capability to predict the source noise level, for every frequency and longitudinal directivity, from individual airframe and engine components and the entire aircraft (Thoma et al., 2023), is then adopted in this project. CHOICE was created from Trafikverket funded project Correlatlon- and physics based preDiction of noise scenaRios (CIDER) and was validated for approach trajectories using flight data recorder (FDR) data and noise measurements from Trafikverket funded project Approach Noise Trials (ANT). Within NEFAT project, additional validations have been performed using ECACdoc29 method which are to be given later in the report.

2.2 Meteorological data

To include the wind conditions in the aircraft operational behavior evaluation and noise propagation assessment, a tool developed in another Trafikeverket funded project En databas med STATistisk METEorologisk data för procedurkonstruktion (STATMET) for computing statistical meteorological data around Arlanda and Landvetter have been integrated with the trajectory model and the noise propagation model. The source of the historical meteorological data of the two airports, Stockholm Arlanda airport and Gothenburg Landvetter airport, were provided by SMHI, which covers an area of 10,000 km² centred around each airport. The meteorological data includes wind speed, wind direction, pressure, humidity, and temperature at 20 altitude levels for each grid point. The altitude levels range from 50 feet up to 15000 feet approximately. The re-analysis data used is available from 1961-2019 but only data from year 2008 to year 2018, has been included in the raw data sources with hourly data recorded for the meteorological variables. Details and relevant study involving the meteorological database and tool can be found in (Zhao et al., 2024).

2.3 Population data

The population data used in this project for evaluating the number of people being affected by the noise generated from aircraft operations near the airport is an information system developed in the

framework of the Global Human Settlement Layer (GHSL) by the European Commission (Schiavina M., 2023). The geospatial population grids in GeoTIFF format have spatial resolutions of 50 m, 100 m, 250 m, and 1 km, while the finest one was adopted.

2.4 Future aircraft concept considered

As first proposed, the major future aircraft concepts considered in the project are limited to electric and hydrogen powered aircraft which could have the potential of removing one of the major noise sources – the conventional engine core. The idea was to connect NEFAT to other projects that Chalmers is involved in regarding future aircraft concepts development. These projects are Swedish national project Sustainable Aviation for Sweden - Technology & Capability Assessment Targeting 2045 (NordicZero) funded by energimyndigheten, Chalmers Area of Advance Transport project Investigation of the impact of technological developments in batteries on Swedish future air transportation (BATSFLY), and EU collaborative project Hydrogen Optimized multi-fuel Propulsion system for clean and silent aircraft (HOPE). Among the three projects, NordicZero has been completed in 2023 while the other two are still on-going.

Results from NordicZero as reported in (Amadori et al., 2023) have illustrated several interesting features in the Scandinavian region in related to future air traffic. With the need of connecting smaller communities more efficiently and easing the impact of geographical hinders on transportation, such as mountains, jagged coastlines, lakes and the Baltic Sea, aircraft with small capacities and short range are desirable. Electric aircraft, if battery technology would be able to fulfill the requirements, and hydrogen fuel cell powered aircraft, are considered the keys towards sustainable aviation. Through projects NordicZero and BASTSFLY, Chalmers has created electric aircraft models as well as an air traffic model, targeting Heart Aerospace's ES-30 top requirements and Swedish domestic air traffic demand. These models are the basis for the future aircraft fleet considered in the project for which the details will be given later in the report.

Hydrogen powered aircraft, on the other hand, have not been included in the studies. Generally, there are two options to use hydrogen as a fuel for aircraft propulsion, either through electrochemical conversion in a fuel cell or by direct combustion in a gas turbine. The current consensus is that fuel cell technology, due to its low specific power, is limited to short range or regional aircraft applications, which is considered similar to an electric powered aircraft. For a larger aircraft, such as A320 class, the study in HOPE project has revealed that the design of hydrogen combustion turbofans is not fundamentally different from a conventional turbofan, while the impact on combustion noise is unclear.

2.5 Noise metrics

The noise metrics used in this report are the commonly used quantitative measures as given below:

- EPNL (dB) – effective perceived noise level, used for aircraft noise certification.
- SEL (dB) – sound exposure level reflecting the total sound energy produced during an event.
- LAmax (dBA) – maximum A-weighted sound pressure level during a measurement period.
- Lden (dB) – an equivalent sound pressure level during a 24-hour period accounting for all sound energy produced by all the flight events during the day, evening and night, considering a penalty for the evening and night operations.

2.6 Multidisciplinary analysis framework

Chalmers Framework for Aircraft Multidisciplinary OptimizationS (FAMOS) based on OpenMDAO (Gray et al., 2019) has been used for interdependencies studies conducted in the project. As illustrated in Figure 1, the calculation process starts with the procedure design and flight performance model which feeds data into the in-house engine performance code, GESTPAN (Grönstedt, 2000), followed by the weight and dimensions estimation tool for the aircraft engine WEICO (Grönstedt et al., 2009) and aircraft design and modelling tool PACElab (PACE Aerospace Engineering & Information Technology GmbH, 2023). NOx emissions are calculated based on a semi-empirical model from AECMA (European Association of Aerospace Industries) (Chandrasekaran & Guha, 2012), implemented in the emission code CHEESE. A system-level noise analysis is then performed using the open-source noise prediction tool CHOICE (Thoma et al., 2023) together with EU GHSL – Global Human Settlement Layer data (Schiavina M., 2023) for estimating the noise-affected population by interpolating the population grid with the noise map. The framework has been used in several studies in the past, such as EU H2020 CENTRELINE and HOPE, where the studies can be found in (Seitz et al., 2021; Thoma et al., 2020; Thoma et al., 2024).

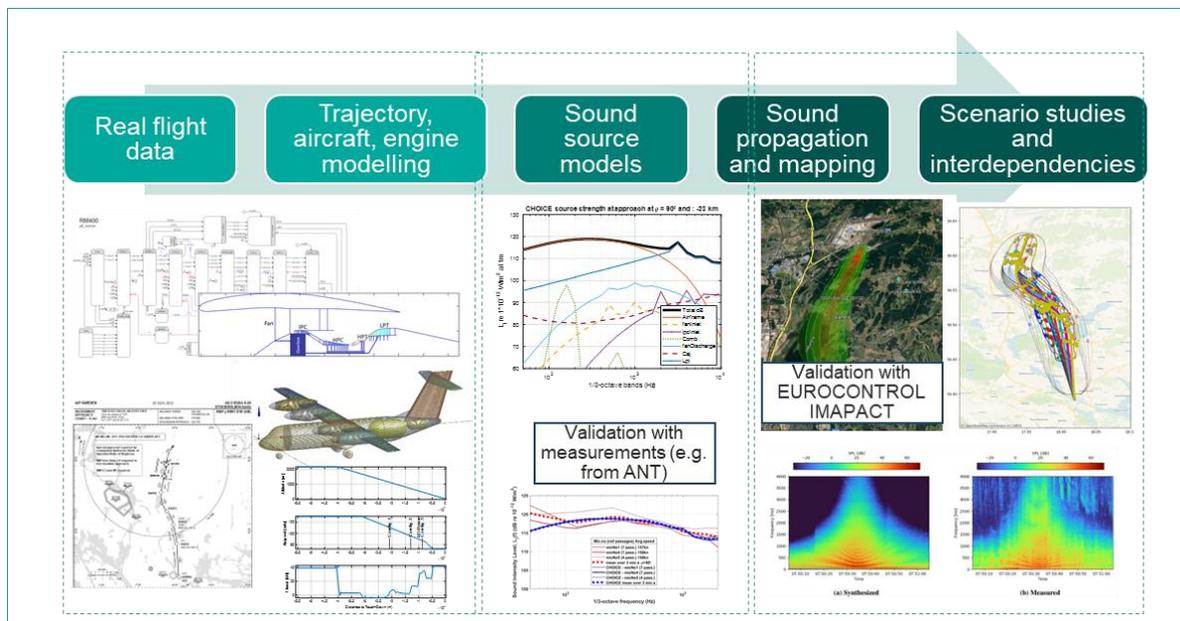


Figure 1 Illustration of noise assessment procedure within Chalmers Framework for Aircraft Multidisciplinary OptimizationS (FAMOS)

3 Results and discussions

3.1 Noise-optimal RNP AR approach procedure

Existing RNP AR procedures at Arlanda airport have been investigated within NEFAT using the methodology as described above to explore the possibility of noise impact reduction. The investigation and optimization have been performed through the design space exploration of the RF turn start point and turning radius. Only A321neo aircraft has been considered as A320 family aircraft are the most flown aircraft to/from the Arlanda airport as reported in (Swedavia, 2023) by Swedavia. Seven procedures, as listed in Table 1, are found in (LFV, 2024) which is published by LFV. Section 3.1 below presents a detailed case study of ESSA RNP_y AR RWY01R while the other six procedures are reported together in Section 3.2. Together with the noise results, fuel burn and emissions changes resulting from the flight path variations have also been calculated. The effect of wind on noise propagation has not been included for the optimizations shown in this section.

Table 1 Existing RNP AR procedures used for optimization

Stockholm Arlanda
ESSA_RNP _y _AR_RWY01L
ESSA_RNP _y _AR_RWY01R
ESSA_RNP _z _AR_RWY01R (updated in 2024 to ESSA RNP _w AR RWY01R)
ESSA_RNP _x _AR_RWY01R
ESSA_RNP _x _AR_RWY19R
ESSA_RNP _y _AR_RWY19R
ESSA_RNP _y _AR_RWY26

3.1.1 Optimization result of ESSA RNP_y AR RWY01R procedure

The procedure of ESSA RNP_y AR RWY01R, both the original chart published by LFV and the reproduced version for optimization, is shown in Figure 2. Throughout the design space exploration, the point of entry to the procedure, AXWAL, was kept fixed and so was the final segment from SA638 until the landing runway, RW01R. The selected design variables were the turn radii of the two turns included in the procedure, with an allowed variation between –2.5 NM and 2.5 NM for each turn. This resulted in a lateral relocation of the waypoints, between AXWAL and SA638. The initial altitude and speed were also kept constant, while the vertical profile was adjusted to each new design, by keeping the same altitude and speed values above each waypoint. The extension of landing gear and high lift devices was controlled by altitude or speed limits.

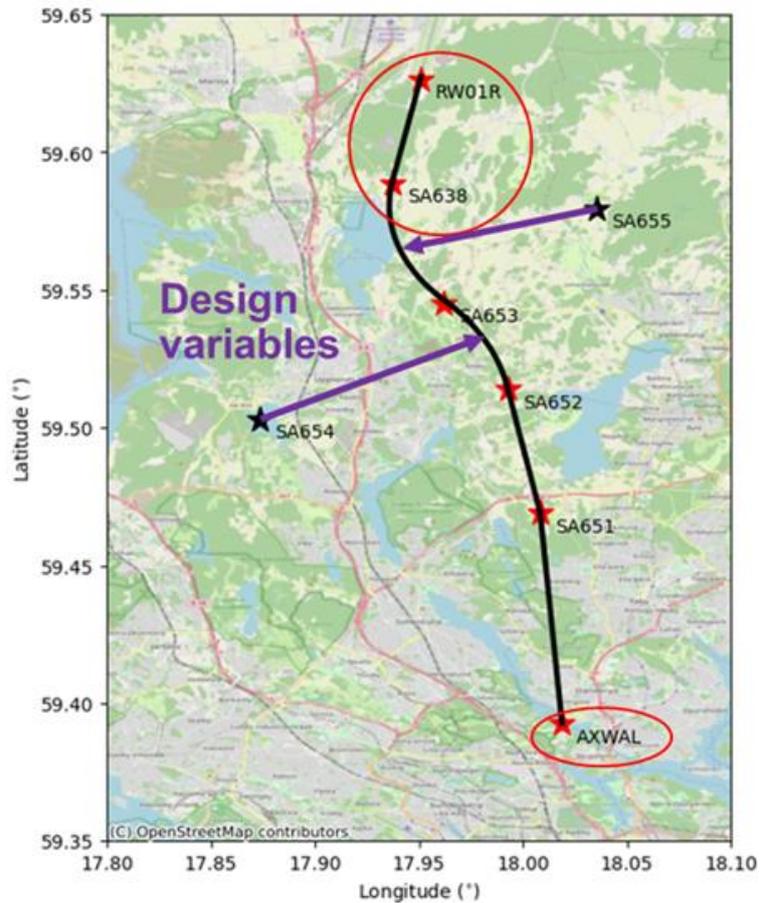
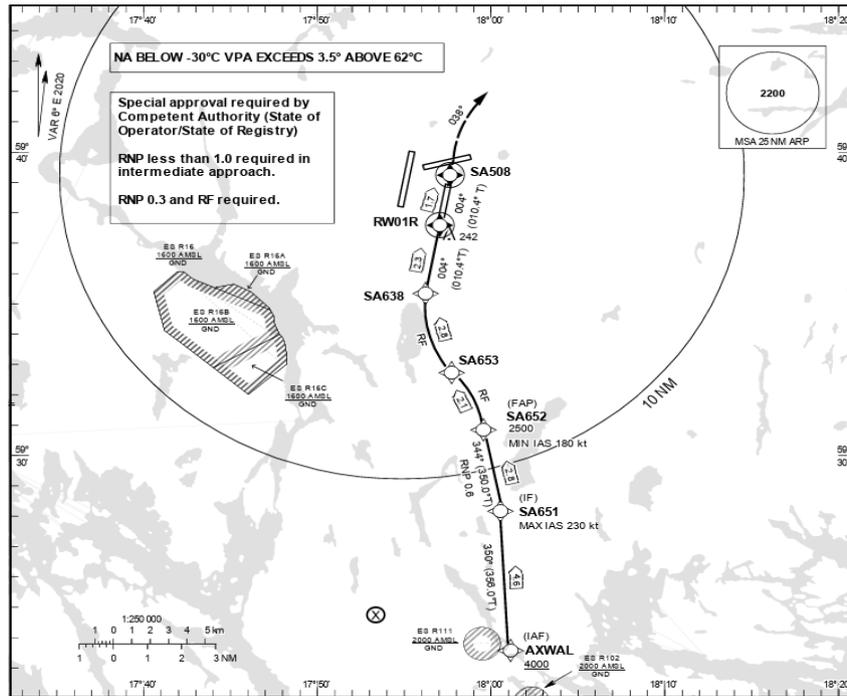


Figure 2 ESSA RNP y RWY 01R (AR) procedure: original from LFV (Top) and reproduced for optimization (Bottom)

The resulting search space is presented on the left side of Figure 3. The horizontal axis indicates the variation in turn radius for the first turn, i.e. the southernmost turn, and the vertical axis

for the second turn. The contour levels represent the amount of population experiencing sound exposure level above 65 dB(A). The existing original procedure design is located on the (0, 0) point where the two dashed lines meet and corresponds to a population of 66318, while the minimum is found where the magenta circle is located, (2.13, -1.79), and corresponds to an affected population of 61271. The white spaces suggest that the design generated by the specified turn radii was discarded either because the descent angle or bank angle limit was exceeded or because it was not possible to design the procedure by keeping the entry point constant.

The two highlighted procedures and the affected population distribution as indicated by colored dots are shown on the right side of Figure 3. As can be seen, in the modified RNP the aircraft first performs a wide turn followed by a narrower turn before aligning with the runway. This results in a shift of the noise footprint towards the northeast and consequently to a reduction in the noise impact for some residents in the more densely populated area located in the west side. In terms of emissions, the two procedures are very similar with a total fuel and NOx mass of 56.4 kg and 615 kg, respectively, for the existing procedure and 56.0 kg and 607 kg for the optimal procedure.

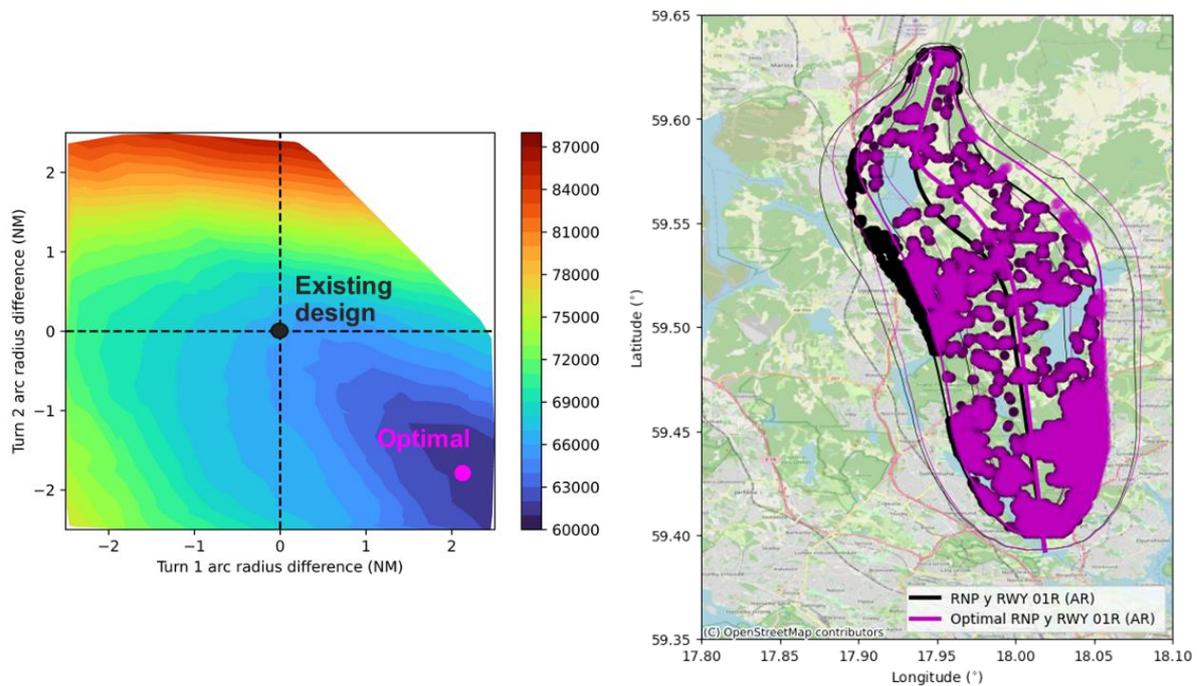


Figure 3 Noise affected population relative to turn radius variation for RNP y RWY 01R (AR) (Left) and the affected population distribution above SEL 65dB(A) from highlighted procedures (Right)

Table 2 Fuel burn, NOx emissions and noise impact for the original existing and optimized ESSA RNP y RWY 01R (AR)

	Existing	Optimal
Fuel (kg)	56.4	56.0
NOx (kg)	615	607
Population affected above 65 dB(A)	66318	61271

3.1.2 Parametric study of other ESSA RNP AR approach procedures

Unlike the design space exploration for the procedure RNP y RWY 01R (AR) as shown in the previous section, the parametric study of the other six RNP AR procedures was conducted using fixed differences of the turning radius from the existing original procedure. This is because the navigation precision specification during RF turn is normally at the level of RNP 0.3, optimization in a smaller step scale does not contribute to an improvement in accuracy but just increase computation load.

3.1.2.1 ESSA RNPz AR RWY01R (updated in 2024 and renamed to ESSA RNPw AR RWY01R)

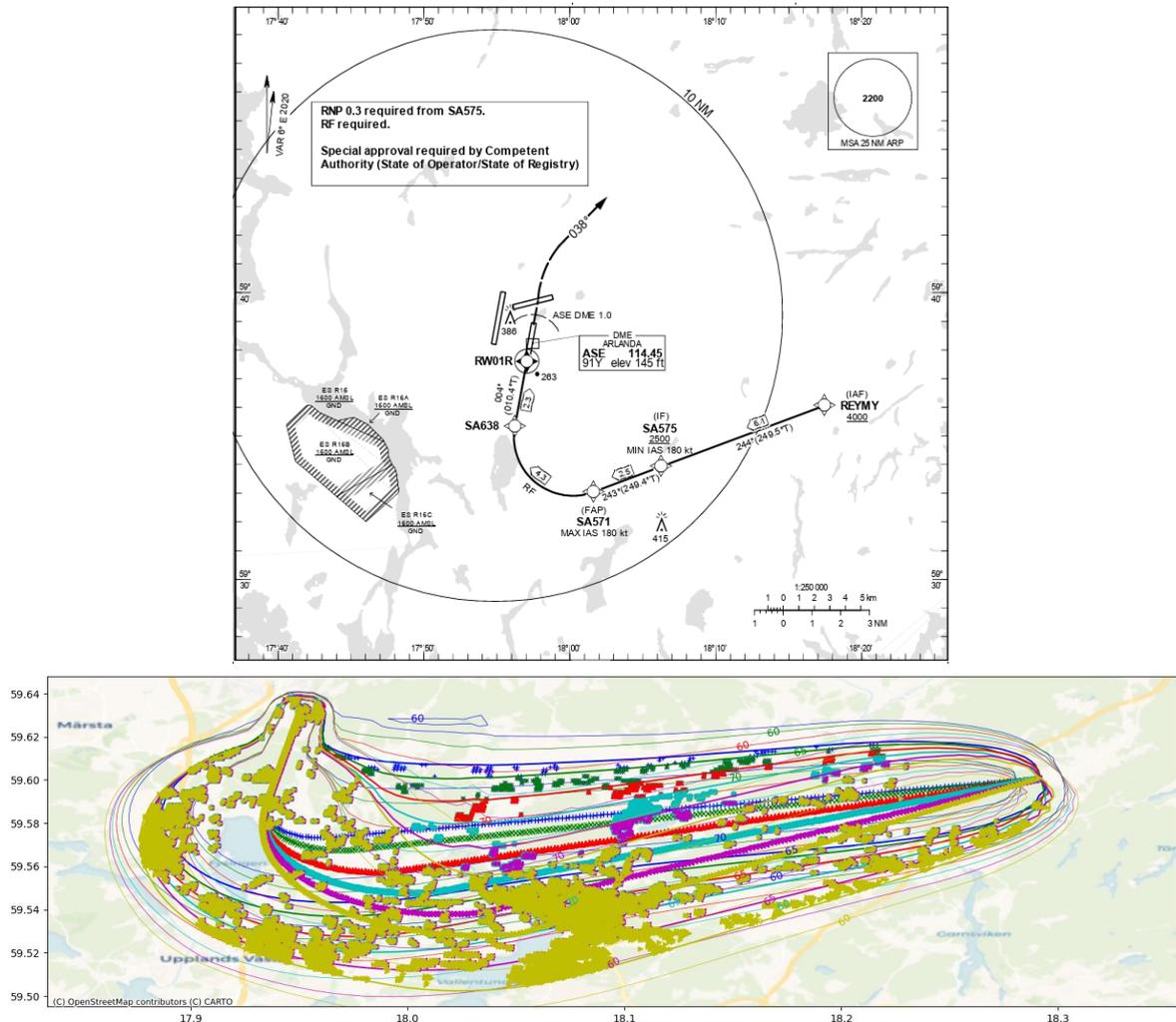


Figure 4 ESSA RNPz RWY 01R AR/RNPw RWY01R AR procedure: original procedure from LfV (Top) and turning radius variation results (Bottom)

From the parametric study result of procedure ESSA RNPz RWY 01R AR/RNPw RWY01R AR as shown in Figure 4 and Table 3, a smaller RF turn radius has the potential of reducing the affected population above SEL 65 dB(A), from 19938 (existing original procedure with turning radius difference 0) down to 3379 (with turning radius reduced by 1.3 NM). In addition, the fuel consumption and emissions are also reduced because of the reduced flight distance. However, as the RF turn radius reduces, the bank angle required may exceed the limit. For a modern aircraft, a standard bank angle limit of 25° should be considered according to the latest regulation document ICAO Doc. 9905 (ICAO, 2021). While the existing original procedures are designed with a relatively high standard tailwind component, one possibility to ease the limit and obtain the benefit is to use statistical wind data as studied in (Zhao et al., 2024).

Table 3 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPz RWY 01R AR/RNPw RWY01R AR procedures with RF turning radius variation

	RF radius -1.3 NM	RF radius -1.0 NM	RF radius -0.5 NM	Existing original	RF radius +0.5 NM	RF radius +1.0 NM
Fuel (kg)	72.78	73.38	75.18	78.05	81.90	84.58
NOx (kg)	0.578	0.581	0.593	0.616	0.648	0.670
CO2 (kg)	230.00	231.87	237.57	246.62	258.80	267.26
Population affected above 65 dB(A)	3379	4063	8797	19938	28580	42880

3.1.2.2 ESSA RNP_y AR RWY01L & ESSA RNP_x AR RWY01R

Procedures ESSA RNP_y RWY01L (AR) and ESSA RNP_x RWY01R (AR), as illustrated on the top of Figure 5, are similar procedures entering the initial approach fix (IAF) from the west of the airport but landing at two parallel runways. As the RF turns in ESSA RNP_x RWY01R (AR) are constrained by the connected track-to-fix (TF) and have limited room for RF turns variation, only the parametric study of ESSA RNP_y RWY01L (AR) has been conducted. The result from the parametric study is given in the bottom plot of Figure 5 and Table 4.

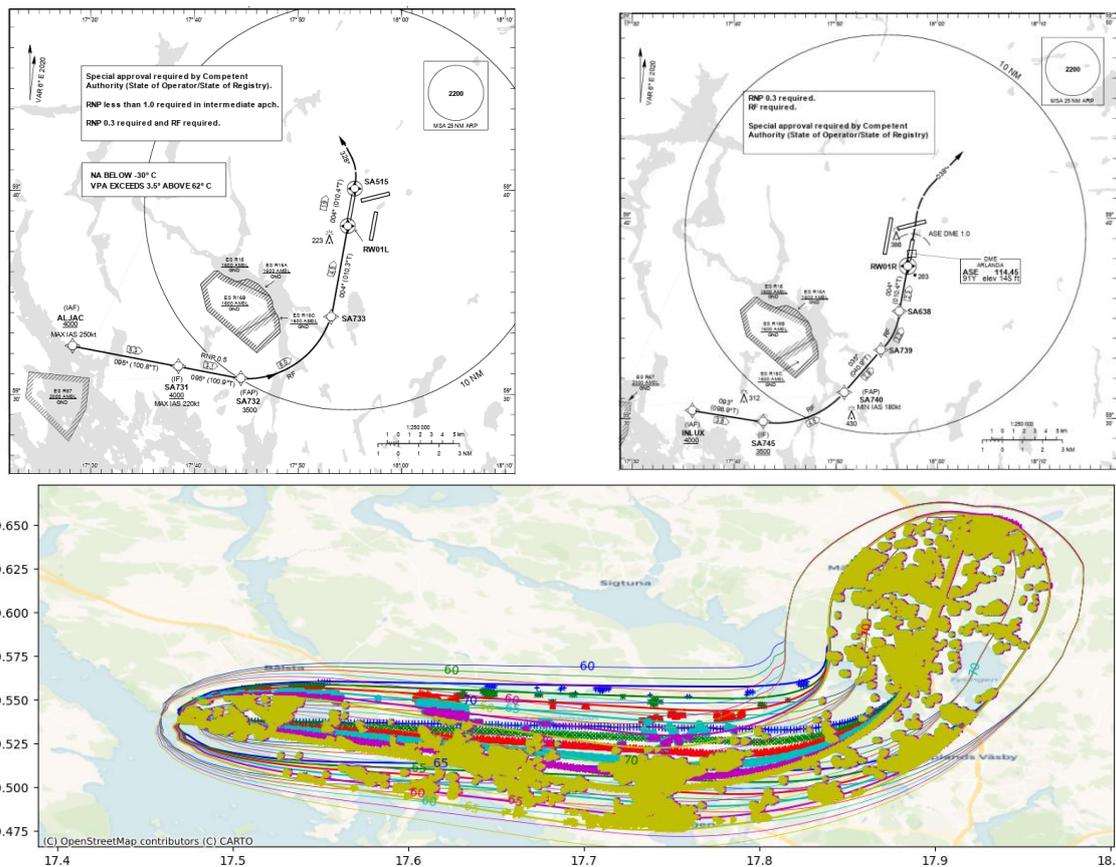


Figure 5 ESSA RNP_y RWY01L AR/RNP_x RWY01R AR procedure: original from LfV (Top) and turning radius variation results for RNP_y RWY01L AR (Bottom)

Similar to the case of ESSA RNPz RWY 01R AR/RNPw RWY01R AR, smaller RF radius has an advantage in reducing the population affected by the aircraft noise, fuel consumption and emissions, but bank angle will be close to limit for the case with minimum turning radius.

Table 4 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPx AR RWY01L procedure with RF turning radius variation

	RF radius -1.5 NM	RF radius -1.0 NM	RF radius -0.5 NM	Existing original	RF radius +0.5 NM	RF radius +1.0 NM
Fuel (kg)	85.56	86.80	88.11	89.30	91.03	92.73
NOx (kg)	0.671	0.683	0.695	0.706	0.721	0.738
CO2 (kg)	270.38	274.30	278.43	282.18	287.65	293.02
Population affected above 65 dB(A)	30675	37215	40296	42143	45293	46981

3.1.2.3 ESSA RNPx AR RWY19R

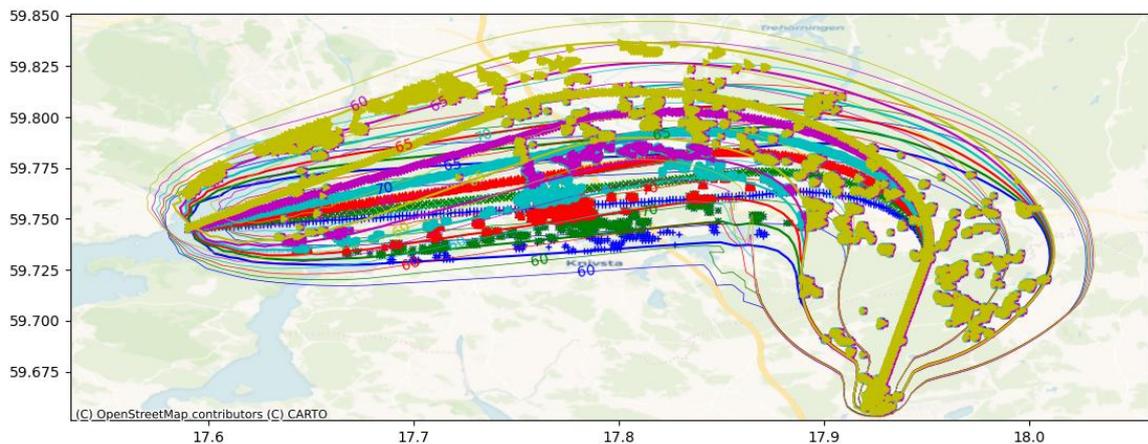
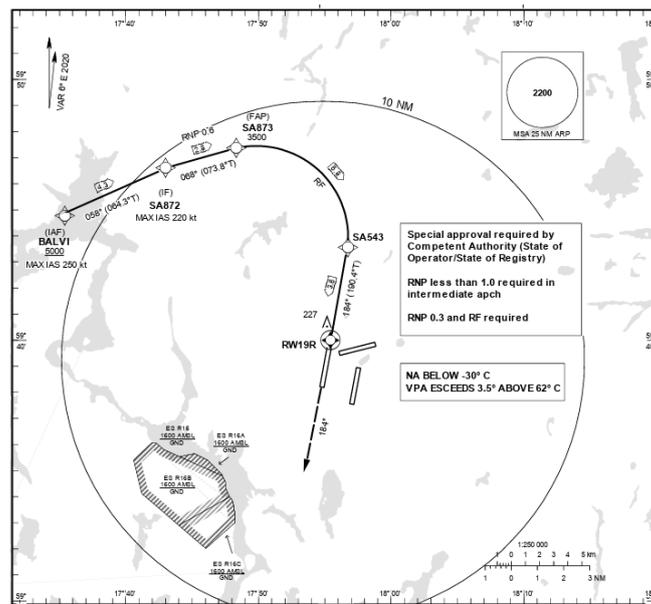


Figure 6 ESSA RNPx RWY19R AR procedure: original from LFV (Top) and turning radius variation results (Bottom)

The original procedure of RNPx RWY19R (AR) can be found in the top figure of Figure 6 with the parametric study results illustrated in the bottom figure as well as

Table 5. The results have shown that the original procedure is close to noise optimal, with a noise affected population of 3457 compared to the lowest case of 3041. Reducing the turning radius could save fuel consumption and lower emissions but would increase the noise impact. Trade-off analysis between these metrics is, however, difficult and would need a common currency. As suggested by the reference group member from Transportstyrelsen, an analytical method measuring the socio-economic cost for the transport sector as presented in (Trafikverket, 2024) can be used but not included in this study as the major target for the project is the noise exposure.

Table 5 Fuel burn, NOx and CO2 emissions, and noise impact for the ESSA RNPx AR RWY19R procedure with RF turning radius variation

	RF radius -1.5 NM	RF radius -1.0 NM	RF radius -0.5 NM	Existing original	RF radius +0.5 NM	RF radius +1.0 NM
Fuel (kg)	77.17	78.87	80.43	82.55	86.15	90.40
NOx (kg)	0.599	0.612	0.622	0.636	0.667	0.705
CO2 (kg)	243.85	249.23	254.15	260.86	272.22	285.67
Population affected above 65 dB(A)	6426	5971	4923	3457	3041	9444

3.1.2.4 ESSA RNPx AR RWY19R

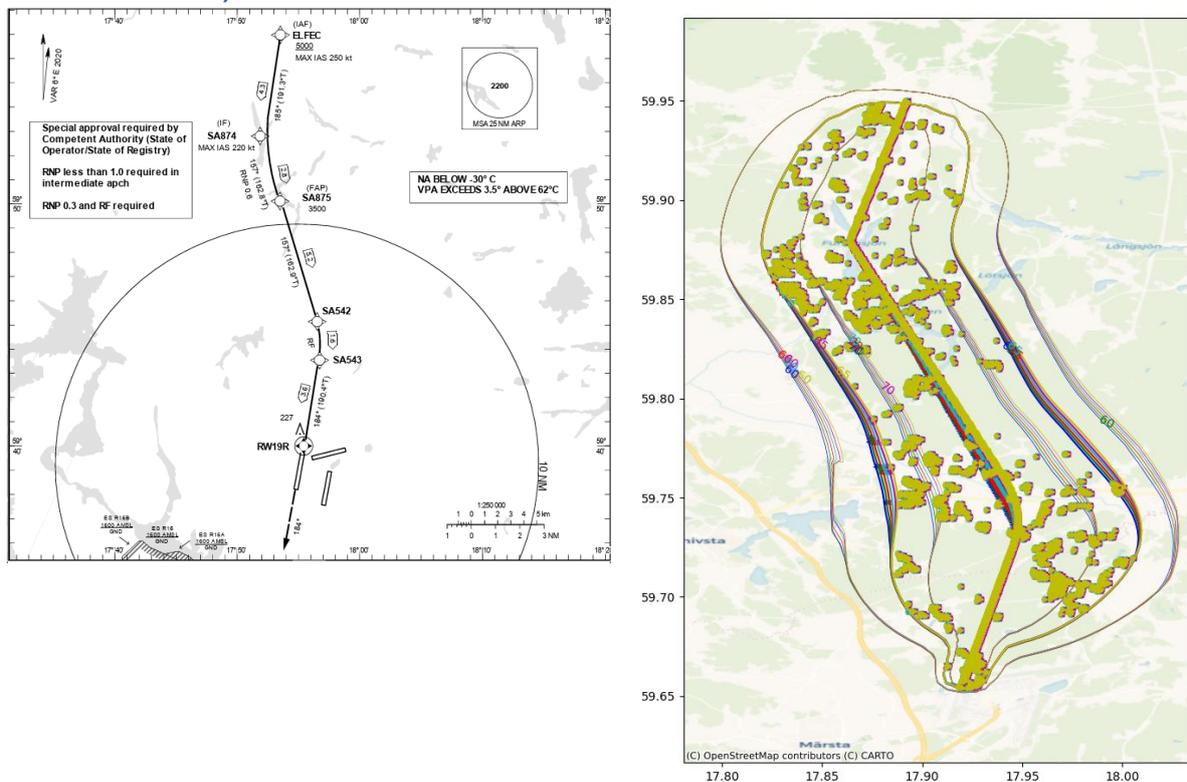


Figure 7 ESSA RNPx RWY19R AR procedure: original from LFV (Left) and turning radius variation results (Right)

The procedure ESSA RNP_y RWY19R (AR) as illustrated in the left figure of Figure 7 presents a relatively straight flight path from the IAF point to the runway. This leads to very limited room for the variation of RF turn radius. Therefore, the changes from the turning radius variation on the population affected by aircraft noise level above 65 dB(A) are nearly unnoticeable.

Table 6 Fuel burn, NO_x and CO₂ emissions, and noise impact for the ESSA RNP_y AR RWY19R procedure with RF turning radius variation

	RF radius -1.5 NM	RF radius -1.0 NM	RF radius -0.5 NM	Existing original	RF radius +0.5 NM	RF radius +1.0 NM
Fuel (kg)	82.72	82.56	82.55	82.54	82.79	82.78
NO _x (kg)	0.639	0.636	0.636	0.636	0.638	0.638
CO ₂ (kg)	261.39	260.89	260.86	260.83	261.63	261.59
Population affected above 65 dB(A)	3492	3466	3460	3443	3439	3411

3.1.2.5 ESSA RNP_y AR RWY26

Because of the relatively sparsely distributed inhabitants along the flight path of the procedure RNP_y RWY26 (AR), the noise impact in terms of population affected from varying the RF turn radius does not change significantly, as shown in Figure 8. Again, smaller turning radius results in shorter flight distances and hence less fuel consumption and emissions. But the tailwind component specified in the regulations document ICAO Doc. 9905 (ICAO, 2021) would again push the bank angle close to the limit.

Table 7 Fuel burn, NO_x and CO₂ emissions, and noise impact for the ESSA RNP_y RWY26 AR procedure with RF turning radius variation

	RF radius -1.5 NM	RF radius -1.0 NM	RF radius -0.5 NM	Existing original	RF radius +0.5 NM	RF radius +1.0 NM
Fuel (kg)	78.58	81.09	84.23	88.47	93.34	99.06
NO _x (kg)	0.608	0.626	0.650	0.685	0.727	0.778
CO ₂ (kg)	248.32	256.25	266.17	279.56	294.94	313.03
Population affected above 65 dB(A)	2005	2068	2140	1990	2031	2138

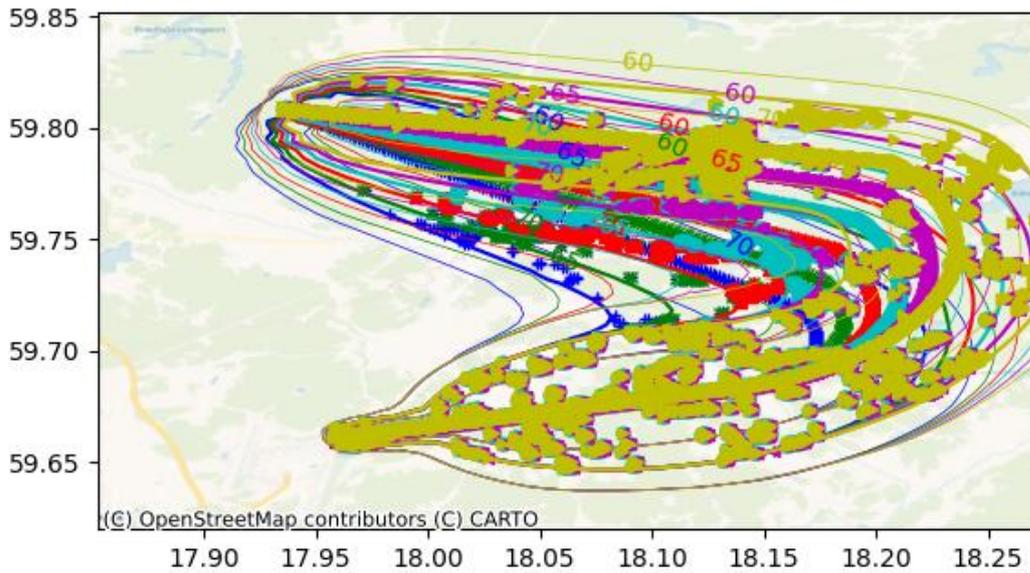
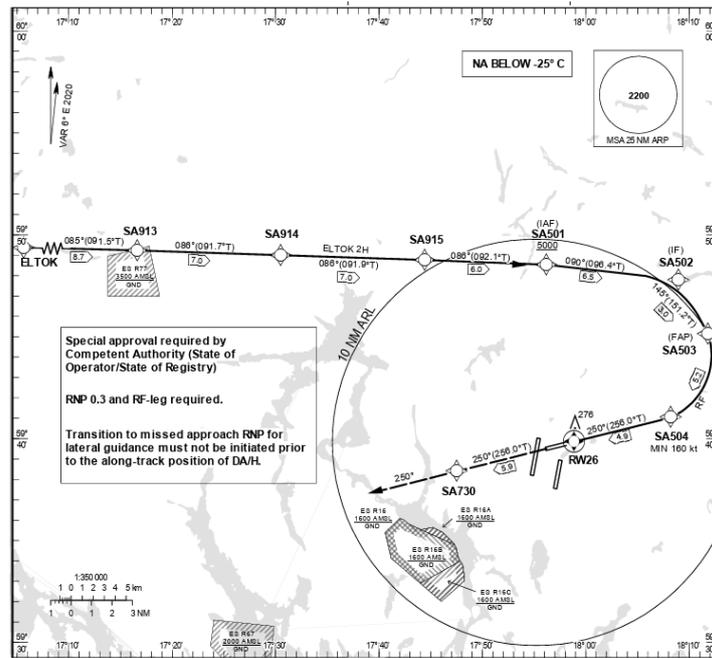


Figure 8 ESSA RNP RWY26 AR procedure: original from LFV (Top) and turning radius variation results (Bottom)

3.2 Noise-optimal RNP AR approach procedure with wind conditions

This section reports two studies regarding the wind impact on aircraft operation and noise propagation. Along with the statistical meteorological wind data bank established within project STATMET (Zhao et al., 2024), a procedure at ESGG Landvetter airport was designed using the meteorological wind data and compared to the same procedure designed using the standard ICAO tailwind component table. The first study shown below compared the noise impact of the two procedures which were designed from different wind data sets. The second study, through applying realistic weather conditions from the STATMET meteorological database to the ESSA RNP_y RWY01R (AR) noise assessment, highlights the impact of wind on the noise propagation and hence on the population affected by the aircraft noise.

3.2.1 Noise from Flight Procedure Designed with Statistical Wind: Auralization and Psychoacoustic Evaluation

A curved approach in a tight left-hand turn for runway 03 at ESGG Göteborg Landvetter airport was designed from statistical wind condition, as displayed in Figure 9 below, within STATMET project. The questions answered within that project were: how to design the procedure with meteorological wind condition and if it is feasible and safe for aircraft operations. This procedure design attempt aimed to replace the existing area navigation (RNAV) STAR procedure for ESGG RWY03 arriving from the north-east, for which the comparison can be seen together on the right-hand side of Figure 9. The green line illustrates the lateral path of the RNP AR (plotted in Google Earth) and the lateral path of the RNAV STAR can be seen in the instrument arrival chart (IAC) that has been inserted as an overlay. From changing the existing RNAV STAR to RNP AR, a significant reduction of 19.4 NM which is about 58% of the RNAV flight distance can be achieved.

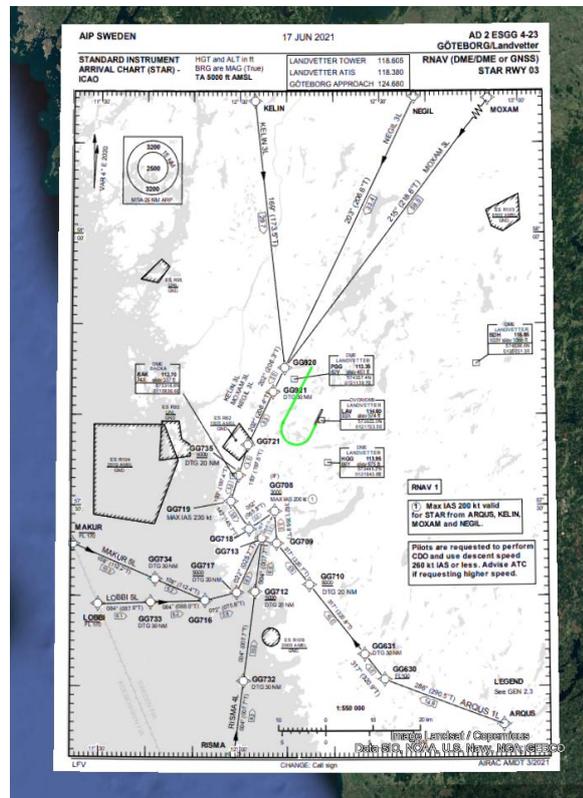
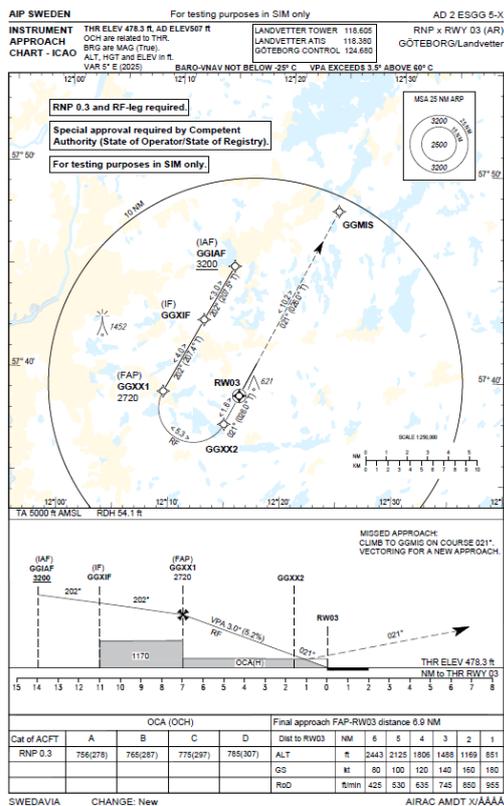
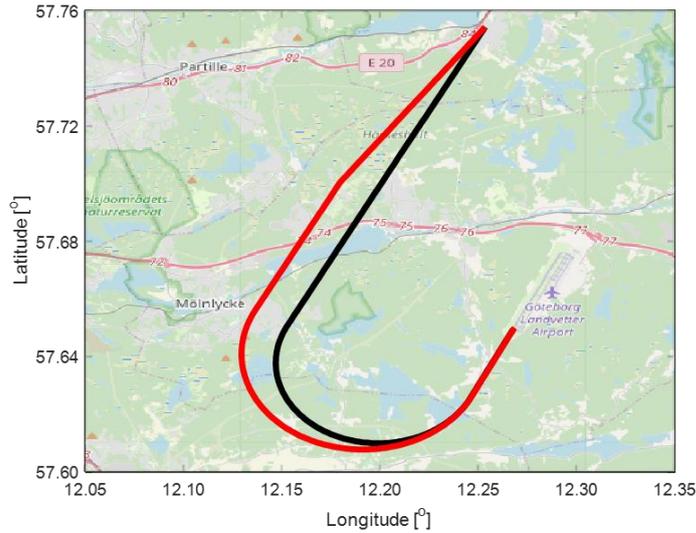


Figure 9 RNP AR approach procedure designed based on statistical wind (Left) and comparison with existing RNAV STAR RWY 03 Closed approach procedure (Right)

RNP AR
with ICAO
standard
wind



RNP AR
with
statistical
wind

Figure 10 Approach procedure design example- RNP AR ESGG RWY 03: with statistical wind (black solid line); with ICAO standard wind (red solid line)

In Figure 10 shown above, the nominal flight path for the RNP AR procedure designed based on ICAO standard wind (red line) as well as the flight path for the RNP AR procedure designed based on the TWC computed by the STATMET demonstrator (black line) are plotted on a map. The flight paths show that with the help of the statistical meteorological wind data from the STATMET demonstrator, the radius of the turn could be reduced and thereby the flight path avoids flying over an inhabited area (Mölnlycke, as can be seen in the zoom-in image of Figure 11). The reduced radius also results in a shorter flight path. Hence, a reduced environmental impact regarding both noise and emissions are expected and the task here is to quantify the benefits.

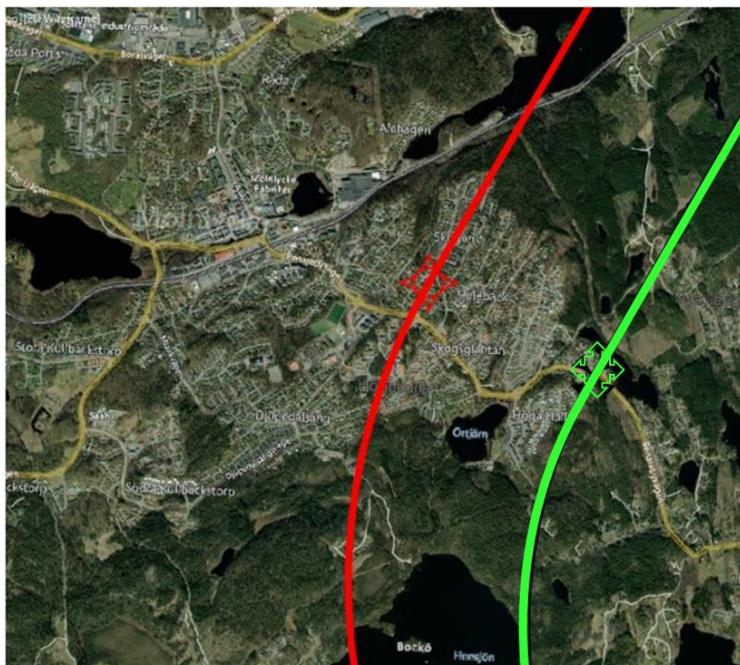
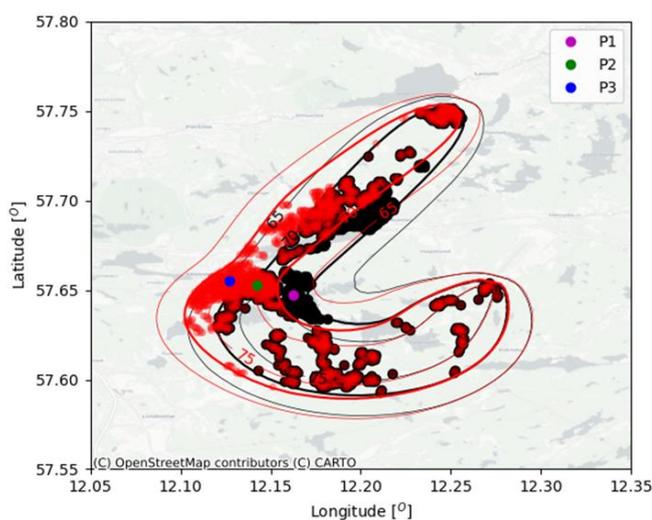


Figure 11 A zoom-in of the RNP AR procedure designed design example- RNP AR ESGG RWY 03: with statistical wind (green solid line); with ICAO standard wind (red solid line)

Table 8 Fuel burn, NOx emissions, and noise impact for the ESSA RNP RWY26 AR procedure with RF turning radius variation

		Standard	Statistical
EPNL (EPNdB)	P1	63.3	73.6
	P2	74.4	73.0
	P3	75.1	65.3
L _{A,max} (dB(A))	P1	52.9	61.6
	P2	62.8	62.2
	P3	63.0	54.7
Affected population		15506	9748
Fuel consumption (kg)		56.8	53.1
NOx emissions (kg)		0.68	0.56
CO2 emissions (kg)		178.4	166.7

RNP AR
with ICAO
standard
wind



RNP AR
with
statistical
wind

Figure 12 SEL contour lines and population exposed to noise level higher than 70 dB(A) depicted as dots for the standard (red) and test procedure (black).

Quantification of the benefits from designing the procedure with statistical meteorological data is given in Table 8 while noise impact results are illustrated in Figure 12. The red and black symbols correspond to the number of people living in an area where the SEL exceeds 70 dB(A) for the existing and the test procedure, respectively. More specifically, the affected population, initially amounting to 15506 people with the standard wind procedure, was reduced by about 5760 people, indicating that the noise contours have shifted towards less densely populated areas. At this point, it is interesting to note that even though the number of affected people decreased, redesigning the flight path results in a relocation of the noise-affected areas meaning that the number of people who were experiencing noise annoyance before will be reduced, but also that people who were not affected before will now be affected by the new procedure. It, therefore, comes down to an ethical dilemma; *should the existing procedure be kept with no effect on the noise-affected population, or should the new procedure be implemented, reducing the total number of affected people but causing*

annoyance for people who were less severely affected before? Questions like this are usually the responsibility of the decision-makers to answer. However, it is important to not only look at the number of people but also to evaluate the noise impact and annoyance in more detail. Although SEL contours are an important and necessary tool for evaluating the noise impact around airports, they do not provide much information on the human perception of the noise and the annoyance experienced by people. It is, therefore, necessary to include tools in the decision-making process that will help in understanding people’s reactions to new procedures. Such tools are for example auralization and psychoacoustic evaluation. The noise spectrograms for the synthesized noise are presented below in Figure 13.

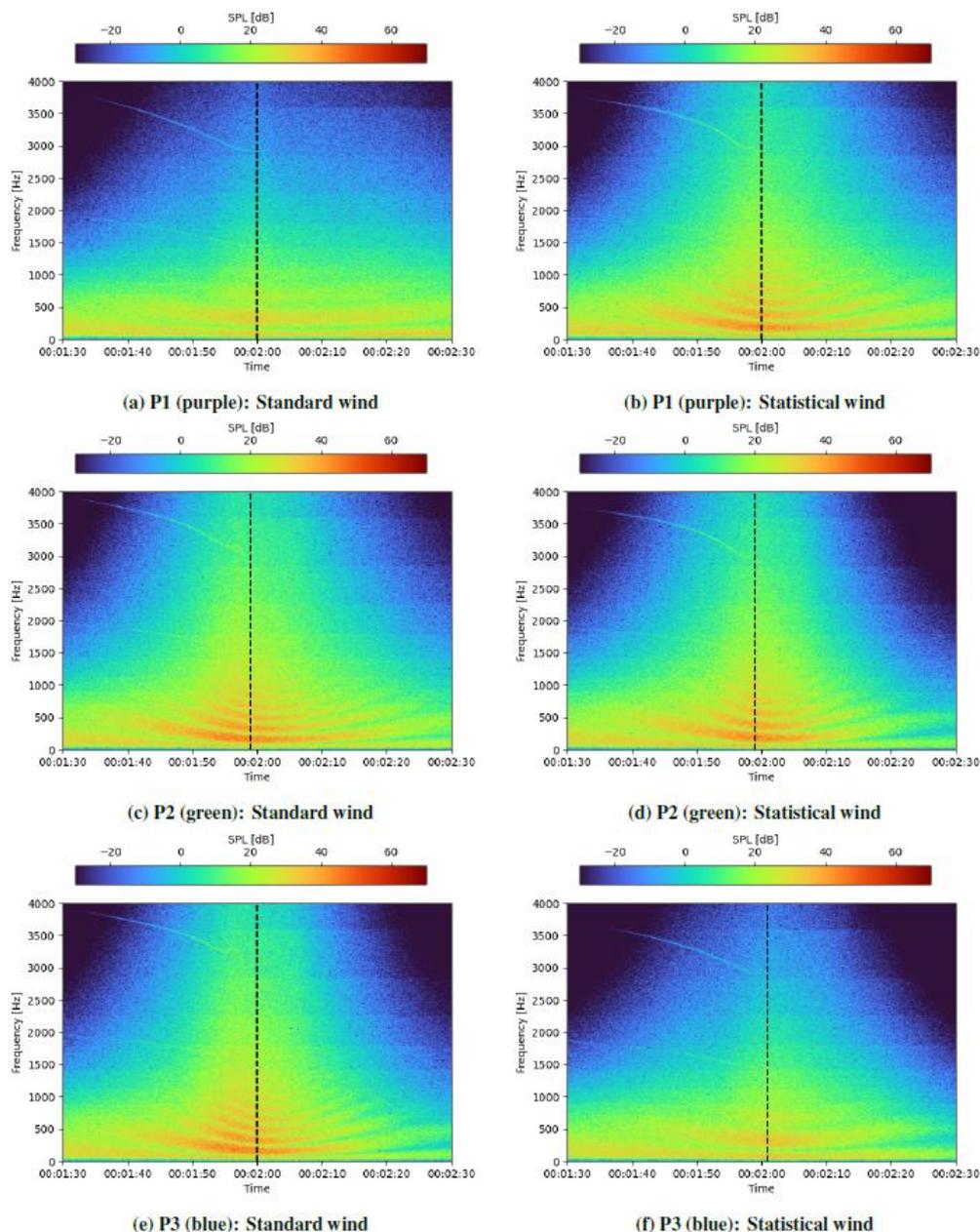


Figure 13 Spectrograms of the synthesized approach noise at the three selected observer points as given in Figure 12

The synthesized noise can be reproduced to audible materials for further investigation, such as psychoacoustic evaluation as shown in Figure 14. Sound Quality Metrics (SQMs) describe the subjective perception of sound by human hearing, unlike the sound pressure level metric, which

quantifies the purely physical magnitude of sound based on the pressure. The five most commonly-used SQMs (Greco et al., 2023) are:

- Loudness (N): Subjective perception of sound magnitude corresponding to the overall sound intensity (International Organization for Standardization, 2017).
- Tonality (K): Measurement of the perceived strength of unmasked tonal energy within a complex sound (Aures, 1985).
- Sharpness (S): Representation of the high-frequency sound content (von Bismarck, 1974).
- Roughness (R): Hearing sensation caused by sounds with modulation frequencies between 15 Hz and 300 Hz (Daniel & Weber, 1997).
- Fluctuation strength (FS): Assessment of slow fluctuations in loudness with modulation frequencies up to 20 Hz, with maximum sensitivity for modulation frequencies around 4 Hz (Osses Vecchi et al., 2016).

These five SQMs were then combined into a single global psychoacoustic annoyance (PA) metric following the model outlined by Di *et al.* (Di et al., 2016). All the SQMs and the PA metric were computed using the open-source MATLAB toolbox SQAT (Sound Quality Analysis Toolbox) v1.0 (Greco et al., 2023). This part of work is a collaboration between Chalmers and TU Delft. As can be seen from Figure 14, in all cases, both the roughness and fluctuation strength metrics remain at relatively low values. The roughness from the standard procedure surpasses all the statistical wind cases, which remain almost unchanged. The low levels of fluctuation strength were expected as the source noise prediction is based on time-averaged models that do not include short-term variations and amplitude modulations caused by atmospheric turbulence. Finally, the global psychoacoustic annoyance metric indicates that for both procedures the annoyance for the two most affected points, i.e. P2 and P3 for the standard case and P1 and P2 for the statistical wind procedure, is almost unchanged, while a slightly lower annoyance level is observed for the two points most affected by the new procedure compared to the points affected by the standard procedure.

3.2.2 Analysis of noise optimal approach procedures with on-site statistical meteorological effects

As described in section 3.1, the optimization and parametric studies were conducted without introducing realistic wind conditions. This was partially because the ray tracing methodology used for accounting wind and temperature profiles in sound ray trajectories calculations is computationally expensive. In addition, determining the appropriate statistical wind and temperature profiles to be used is an unsolved open issue. In this case, aiming at demonstrating the importance of wind conditions on noise propagation, historical meteorological data from the location of the procedure were applied to the study of ESSA RNP_y RWY01R (AR) as presented in 3.1.1. The data were collected over a 10-year period from 2008 to 2018 and calculated from STATMET demonstrator. From the down-selected data, the maximum 95th percentile wind speed was chosen and only a variation with altitude was assumed. For the temperature, the 95th percentile value of all years was used. The selected data resulted in a temperature of 20.9 °C at mean sea level and a wind speed of 18.7 kt from north to northwest (wind direction of 350 degrees) at a height of 35 m above the ground.

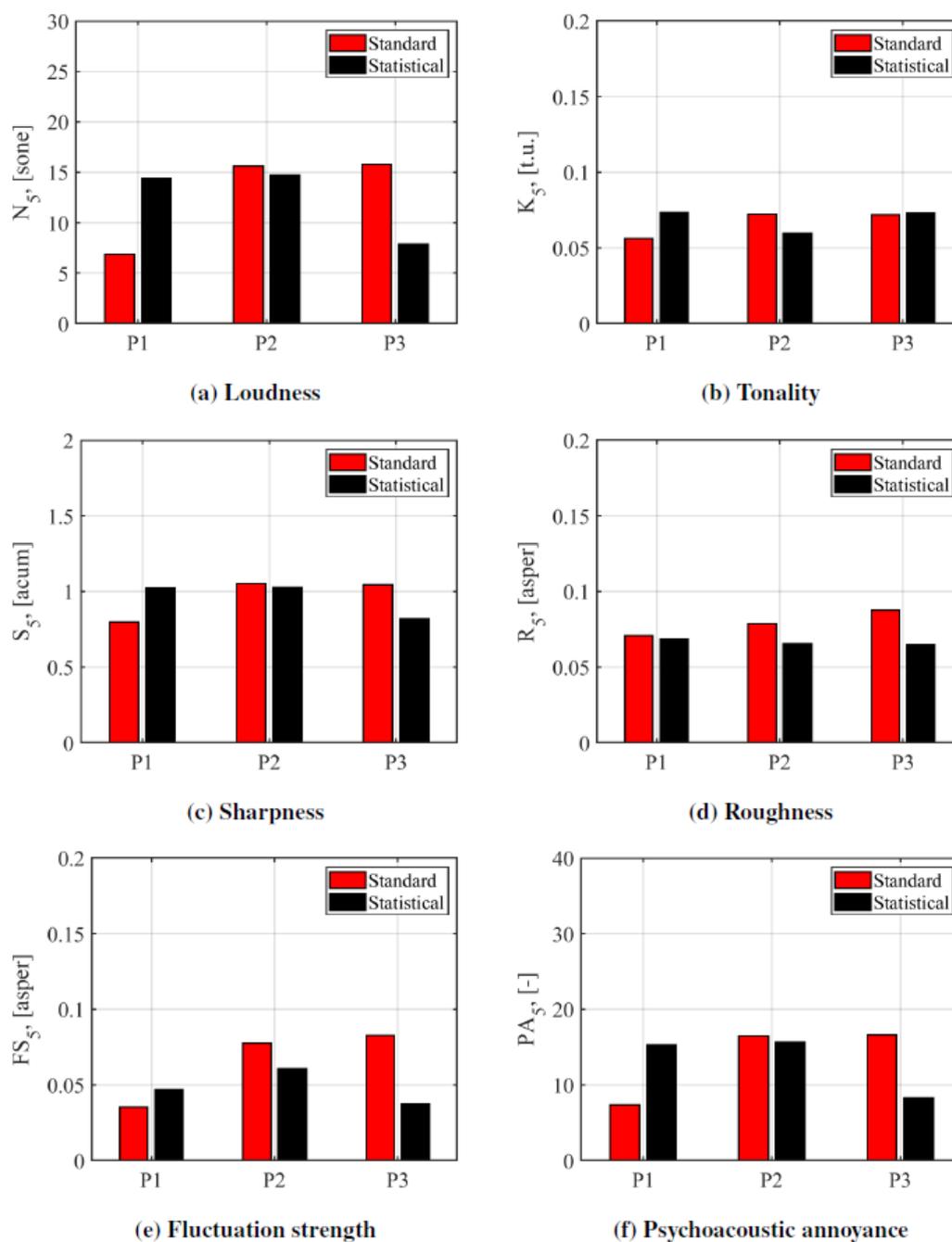


Figure 14 Sound quality metrics for the three selected points and two procedures considered.

The resulting sound exposure contours are presented in Figure 15. In both cases, the effect of the wind is evident as the contour maps indicate a higher spreading towards the south. In this case, the number of people affected by the existing RNP is 150082 while for the optimal procedure the affected population decreases to 149754. These numbers are significantly increased compared to those presented in Section 3.1. This is mainly attributed to the temperature difference, as for the selected conditions the atmospheric temperature is 5.9 °C higher compared to the ISA temperature used for the results in the previous section, leading to lower atmospheric absorption and therefore increased noise level on the ground. If, for example, only the temperature would be accounted for, i.e. zero wind and propagation without consideration of wind and temperature gradients, the affected population for the existing and the optimal procedure would equal 122711 and 118250, respectively.

The remaining difference in noise-affected population can be attributed to the effect of the wind as well as differences in performance characteristics. As the path of the procedure and the true airspeed of the aircraft are kept constant under all conditions, higher power requirement is required when the statistical data are used due to the strong headwind. This increased thrust level hence results in a higher noise level emitted by the aircraft.

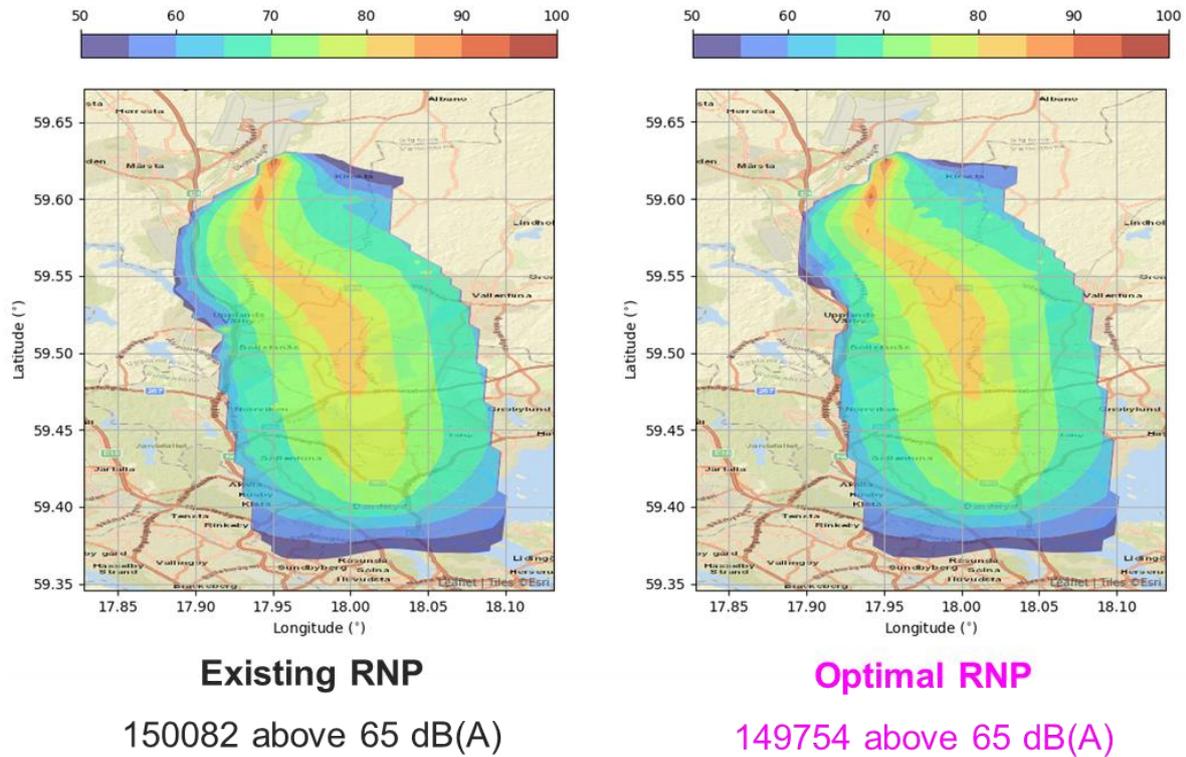


Figure 15 SEL contours for the existing and optimal procedures from Section 3.1.1 with weather conditions.

From Figure 15, it can be observed that the modified RNP results in the displacement of the noise-affected area towards the northeast which is less densely populated. However, the shape and areas of the different noise levels have also been changed, indicating that the noise level in certain areas, especially those located in the inner side of the steep turn, might have increased. A detailed analysis of the noise-affected population for the different noise levels and conditions is presented in Table 9. In the same table, the total consumed fuel and NO_x mass can also be seen. Interestingly, under the statistical weather conditions, the noise from the optimal procedure seems to affect fewer people in all cases apart from the 75 dB(A) level, while under ISA conditions more people are affected from the 75 dB(A) and 80 dB(A) level, compared to the existing procedure. In terms of emissions, the two procedures are very similar, indicating that improved noise impact can be achieved without sacrificing emissions. The higher emissions observed under the statistical conditions can be partly attributed to the higher atmospheric temperature as well as to the increased power requirement, as seen in Figure 5. Furthermore, due to the lower ground speed, the flight time is increased by about 80 seconds, resulting in a further increase in emissions. It becomes evident that it is important to consider local weather conditions when procedures are designed as the impact of each procedure might vary depending on the conditions. This analysis should perhaps be complemented with the impact that each noise level would have on human health in order to draw more concrete conclusions as to which procedure would be more beneficial.

Table 9 Fuel burn, NOx emissions, and noise impact for the ESSA RNP RWY01R (AR) procedures with statistical weather conditions and ISA conditions

SEL (dB(A))	Statistical weather conditions		ISA conditions	
	Existing	Optimal	Existing	Optimal
65	150082	149754	66318	61271
70	63802	59956	19623	19377
75	15309	15554	1773	1806
80	1169	1001	410	459
Fuel (kg)	79.9	79.5	56.4	56.0
NOx (kg)	964	956	615	607

3.3 Noise mapping for the future aircraft fleet

This section reports the study of noise mapping considering a future aircraft fleet which is composed of future hybrid/electric aircraft and modern conventional aircraft. The subsections below will firstly describe the aircraft fleet modelling followed by its noise mapping results.

3.3.1 Aircraft fleet modelling with hybrid/electric aircraft

3.3.1.1 Hybrid/electric aircraft model

The hybrid/electric aircraft model has been built from Heat Aerospace ES-30 top requirements (HeartAerospace, 2025) and retrofitted from Dornier 328 as shown in Figure 16 using commercial aircraft modelling tool Pacelab. The passenger capacity of the hybrid electric aircraft is set to 25 passengers initially with an upgrade to 30 passengers as listed in

Table 10, which is much lower than that of modern regional aircraft. This is mainly limited by the specific energy density of batteries, while increasing passenger capacity to the next level, 50 or even 76 passengers, would either make the range of the aircraft too short or the aircraft too heavy. The entry into service year for the aircraft is set at 2030 with an initial production rate per year as 20 and 10% increase in production rate per year is assumed. More importantly, the range for the first version of the electric aircraft is limited to 200 km while the hybrid version is set to 400 km. With these assumptions, the number of hybrid/electric aircraft flights as reported in the 2035 fleet and air traffic model given in later section is calculated based on the travel demand with range lower than 400 km. For the 2050A fleet and air traffic scenario, the upgraded full electric aircraft is assumed capable of conducting missions with range requirement up to 800 km. For the missions beyond 800 km, i.e. from Stockholm to Kiruna, one transfer is added to force the air traffic model to use only electric aircraft.



Figure 16 Hybrid/electric aircraft model retrofitted from Dornier 328

Table 10 Hybrid/electric aircraft model parameters

PARAMETER	UNIT	HYBRID/ELECTRIC	FULL ELECTRIC
Entry into service	year	2030	-
Initial production rate	per year	20	-
Production rate increase	per year	10%	-
Design range	km	200 full electric 400 hybrid	800
Design PAX	-	25	30

3.3.1.2 Fleet and air traffic model

The fleet composition is constructed based on the environment report published by Stockholm Arlanda airport (Swedavia, 2023). From the report, the most operated aircraft at Arlanda airport are

the A320 family and B737 family aircraft followed by CRJ9, ATR72 and Fokker 50, and other types of aircraft. For simplicity, an A320neo aircraft model has been used to represent B738, A20N, A320, A321, A319 and A21N while an ATR72 aircraft model has been selected for representing regional aircraft in general. In addition, the same runway usage distribution has been adopted as reported in (Swedavia, 2023).

While only domestic flights are considered, the travel data published by Transportstyrelsen (Transportstyrelsen, 2024) are collected for the flight fleet establishment. Start from historical domestic flight data for 2024, assuming an average travel demand increase rate of 1.3% which is extracted from the base scenario in EUROCONTROL's Aviation Outlook 2050 report (Eurocontrol, 2022) for Sweden, four scenarios have been created. The air traffic and fleet model data for the four scenarios are given in Table 11.

- 2024 – baseline with historical travel data and modern fleet composition without hybrid/electric aircraft
- 2035 – 5 years after the introduction of hybrid/electric aircraft. Routes which cannot be covered by the range of the hybrid/electric 2030 aircraft will be operated with A320neo and ATR72.
- 2050A – Long term prediction, full electric aircraft only.
- 2050B – Long term prediction, modern conventional aircraft only.

Table 11 Air traffic and fleet model data used for aircraft fleet noise assessment at Arlanda airport

DOMESTIC TRAVEL	2024	2035	2050A	2050B
No. Passengers per year	2031871*	2342073	2842773	2842773
No. Arrivals per year/per day	27352/67	129980/306	190487/452	34310/94
No. A320neo flight per day	40	13	-	56
No. ATR72 flight per day	27	10	-	38
No. hybrid/electric flight per day	-	283	452	-

3.3.2 Impact of future aircraft concepts on noise mapping from aircraft fleet operation

Results of the equivalent sound pressure level during the day, evening and night Lden from the four scenarios as defined in previous section accounting for the noise impact of all the flight events in a day are shown in Figure 17. For the 2024 case, a comparison between the resulting Lden contour and the result produced from ECACdoc29 method is given in the next section where a good comparison can be observed. With the introduction of the hybrid/electric aircraft from year 2030, for the 2035 case, the hybrid/electric flights can take a considerable large portion of the total domestic travel demands from/to Stockholm Arlanda airport, which is of course beneficial to the environment from the inflight emissions perspective. However, the noise assessment indicates the opposite effect as can be seen from the two contours at the top of Figure 17 where a significant increase in both the intensity of the noise levels and the area covered by noticeable noise levels is presented. This consequence is mainly a result of an increasing travel demand assumption as well as the much smaller passenger capacity of hybrid/electric aircraft. Due to technology limit, especially the energy density of the

electric energy storage system, electric aircraft will have much less passenger capacity compared to conventional regional and single aisle aircraft. This will lead to more frequent departures and landings, about 4.5 times more flights, assuming an increasing travel demand in the future, hence a much more severe noise footprint.

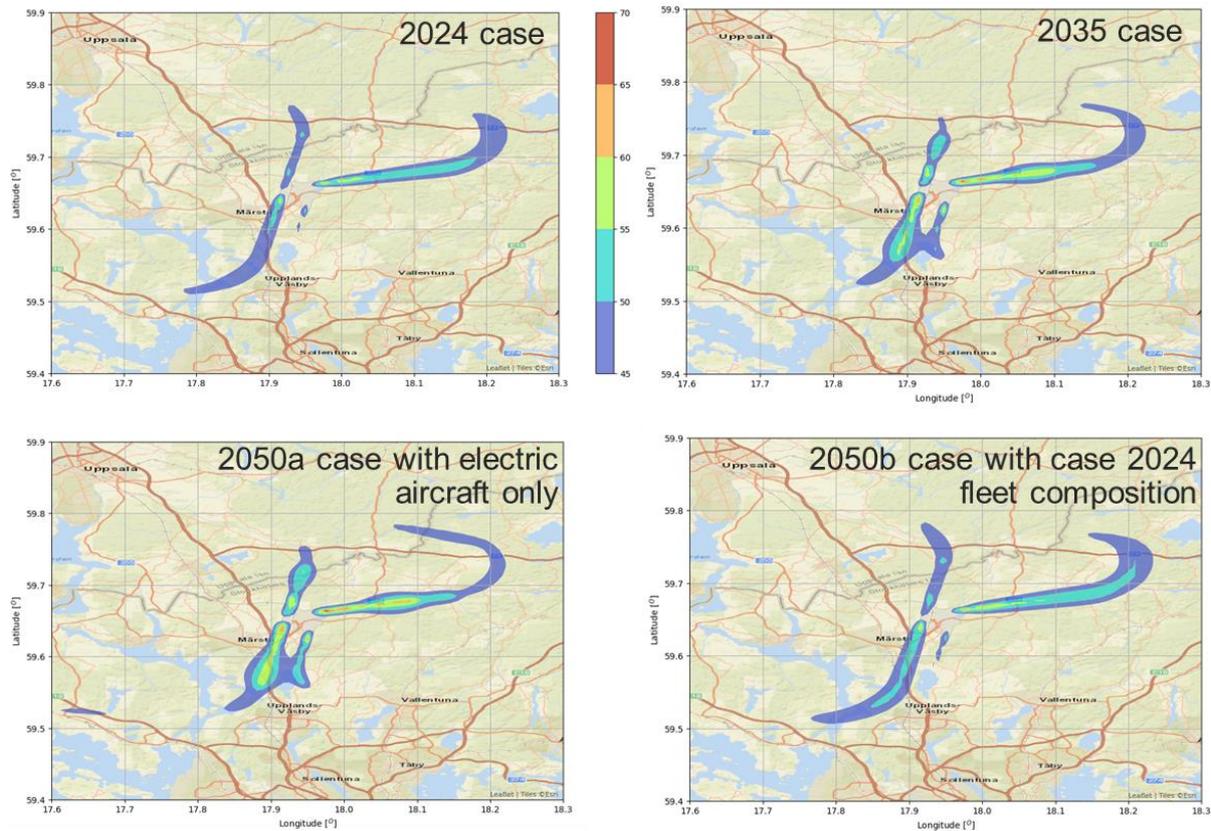


Figure 17 Lden contours for the four scenarios as defined in Table 11

Moving to 2050 and looking at the two contours positioned at the bottom of Figure 17, full electric air traffic scenario 2050A shows a solid increase in noise emissions compared to the 2035 case. On the other hand, if the modern conventional fleet composition remains towards 2050, see the 2050B case contour, the noise impact will be larger compared to the 2024 case, but at a slower pace compared to the electric aircraft introduction. Comparing 2050A and 2050B case directly, the larger aircraft represented by the modern conventional fleet may have its noise noticed earlier as indicated by the longer strips in the contour. However, it would be less noisy as the high lift devices and landing gears are used less, which is obviously proportional to the number of arrivals.

3.4 Validation

Validation has been performed for the noise assessments of the A320neo aircraft and the ATR72 aircraft against ECACdoc29 method. The hybrid/electric aircraft noise modelling, however, can not be validated since no valid source can be found. The comparisons are shown in Figure 18 - Figure 21, where Figure 18 - Figure 20 are for A320neo case flying three RNP procedures at Arlanda airport and Figure 21 is for ATR72 flying one RNP procedure at Arlanda airport. In general, the noise contours are similar for the same case calculated from ECACdoc29 method and FAMOS/CHOICE. The sound exposure levels match very well from the aircraft entering the IAF of each procedure down to the touch down at runways.

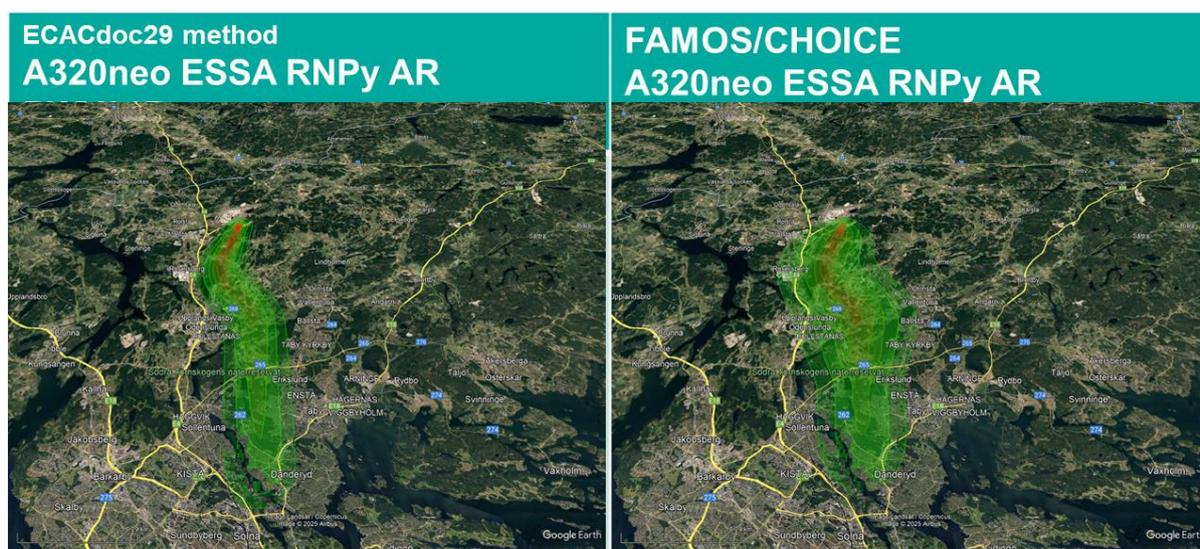


Figure 18 Comparison of ESSA RNP Y RYW01R AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right)

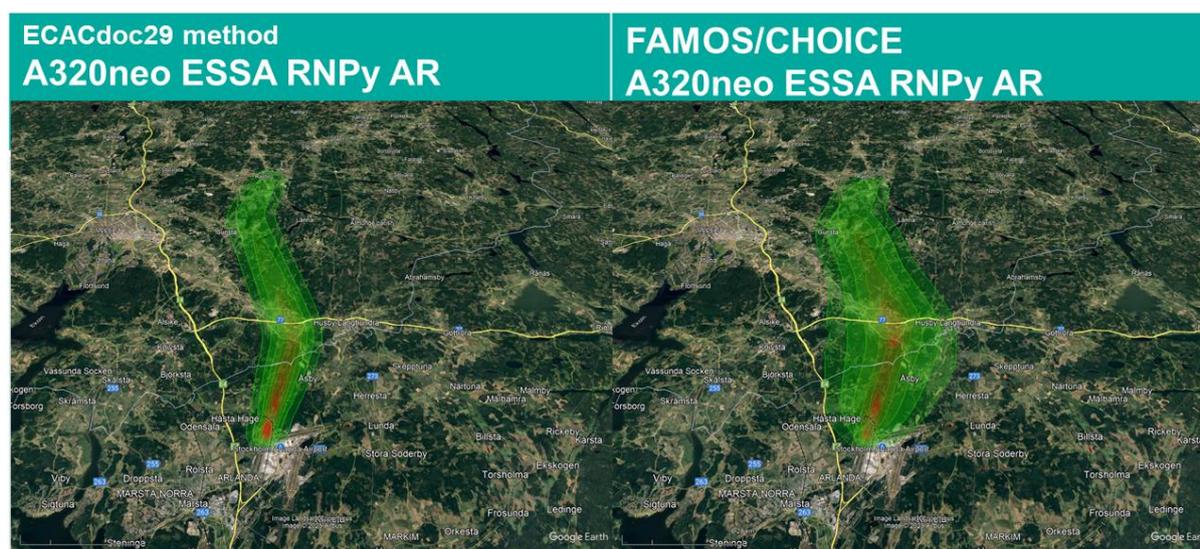


Figure 19 Comparison of ESSA RNP Y RYW19R AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right)

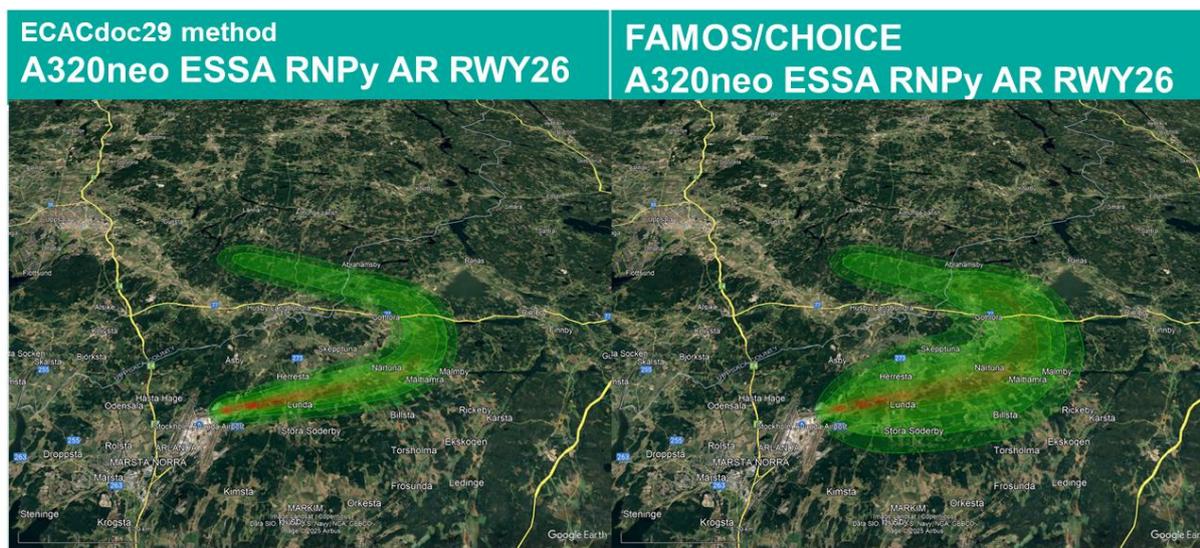


Figure 20 Comparison of ESSA RNP γ RYW26 AR single event noise mapping of A320neo from ECACdoc29 method (left) and FAMOS/CHOICE (right)

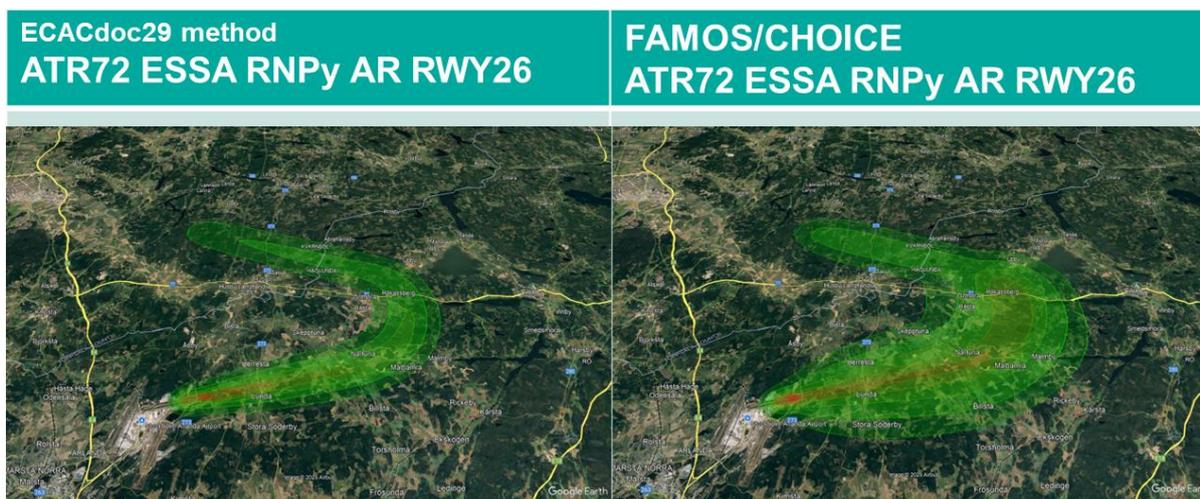


Figure 21 Comparison of ESSA RNP γ RYW26 AR single event noise mapping of ATR72 from ECACdoc29 method (left) and FAMOS/CHOICE (right)

The major difference revealed from the comparisons is that the areas covered by each noise level contours predicted by FAMOS/CHOICE are much larger than that of ECACdoc29 method. This is in particular obvious after the aircraft flies over the initial part of the procedure with clean configuration. When the flaps/slats and landing gears started to be deployed, the semi-empirical airframe noise model implemented within CHOICE tends to predict a higher noise level than ECACdoc29 method does. Since the CHOICE noise model requires more detailed input parameters of the high lift devices and landing gear deployment timing, the difference should be expected as ECACdoc29 method relies more on noise, power and distance relationships.

In addition to the direct comparisons of the two tools, studies exist comparing the two tools with measurements separately. For ECAC Doc 29 method, a validation study conducted in (Lautsch et al., 2024) has shown that the method tends to underestimate the noise levels especially for arrival events compared to the measurements of the noise monitoring system at Hanover Airport. On the other hand, the validation study for CHOICE can be found in (Thoma et al., 2023). One of the comparisons between the synthesized noise computed from CHOICE and the measurements from

Trafikverket funded project ANT (Åbom et al., 2021) is presented in Figure 22. As it can be seen from the chart, the noise levels computed from CHOICE match well with the recording. The major difference from time 08:48:30 is because of birds singing close to the microphone which can be clearly heard from the recording.

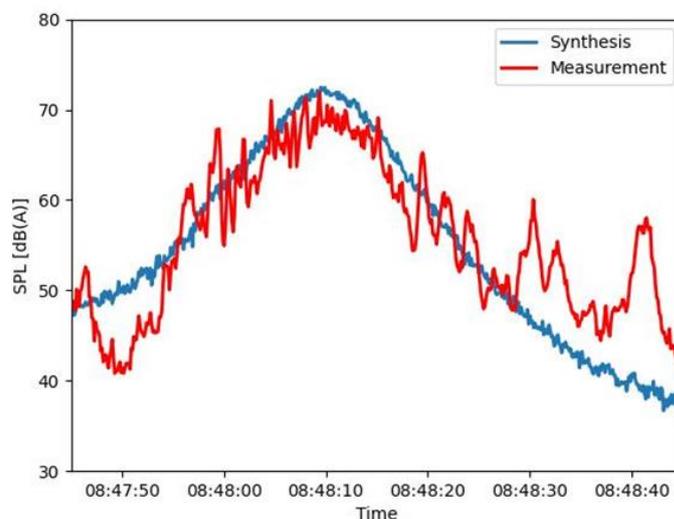


Figure 22 Comparison between the synthesized noise computed from CHOICE and measured noise from ANT project

Since no valid source of hybrid/electric aircraft noise can be found in public, the comparison of the Lden calculations from ECACdoc29 method and CHOICE has been made using the 2024 scenario case with the modern conventional aircraft fleet. The comparison is shown in Figure 23. As expected from the single event result, CHOICE predicts larger area for a certain Lden level. Interestingly, concentrated red spots on the runways can be observed from the ECACdoc29 method results. A plausible reason for this is that CHOICE only simulates approach procedures until touch down so it misses the noise peaks that occur on the runways. However, this is not considered critical, and it is not a must-capture phenomenon as the focus has been put on the inhabitants living near the airport.

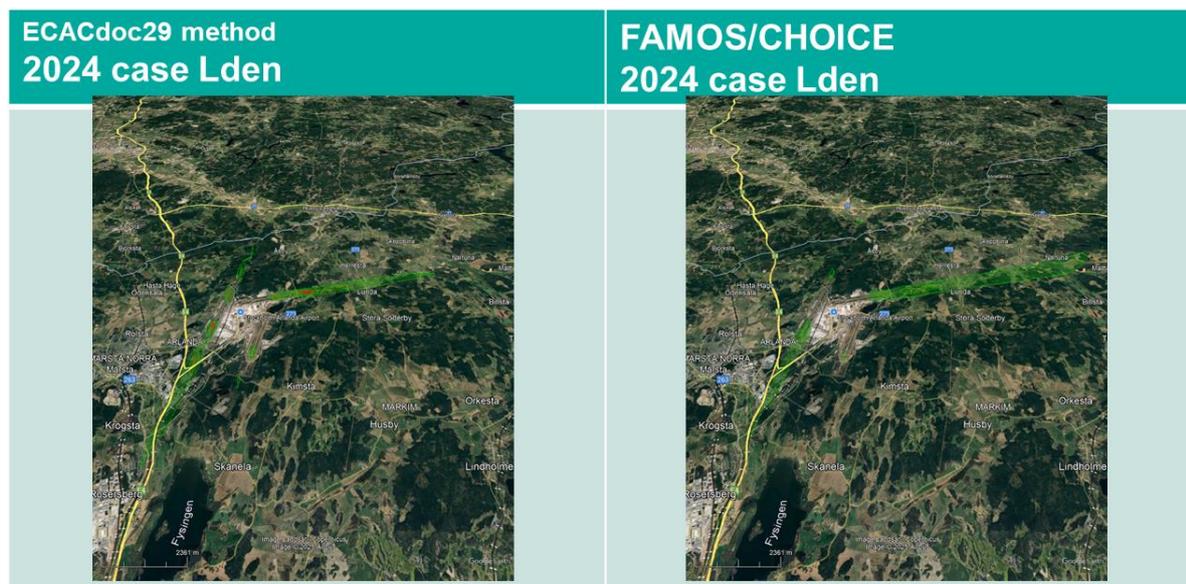


Figure 23 Comparison of Lden contour of 2024 scenario case from ECACdoc29 method (left) and FAMOS/CHOICE (right)

4 Conclusions and recommendations

In conclusion, existing RNP AR APCH procedures at the two major Swedish airports are well designed in balancing noise, emissions and fuel consumption under current practical constraints and regulations. Opportunities for further improvements in noise footprint rely on the use of historical meteorological information for the location of the procedure, which is documented in RNP AR procedure design manual but not implemented yet. Depending on the specific case, the use of meteorological wind data into procedure design could reduce the population affected by single event noise levels (SEL) above 65 dB by 37% (ESGG RNP x RWY03), 7.6% (ESSA RNP y RWY 01R), and up to 80% (ESSA RNP z RWY 01R/RNP w RWY01R).

The realistic meteorological data, on the other hand, introduces high complexity in the noise assessment of the flight procedures as it affects aircraft and engine performance as well as noise propagation. While the example case for ESSA RNP y RWY 01R demonstrates that identical weather profiles would affect the optimal and existing ESSA RNP y RWY 01R similarly, the magnitude of this effect cannot be overlooked. The selected head wind and slightly warm condition could amplify the noise impact by several times from the simulation results. The practical use of flight paths optimized with weather data, either statistical or real-time, may be challenging but could be possible in the future with AI assistance.

Regarding future fleet, the study carried out has been biased towards electric air traffic network. However, the simulation result discourages the use of electric aircraft for all travels unless a similar level of passenger capacity of modern aircraft could be met by the electric aircraft, from noise footprint perspective. That would rely on the development of more advanced battery technologies for a much higher specific energy. To use more spatially distributed small airports instead of centralized big airports may be another solution but air traffic control could be challenging. In addition, spatially distributed small airports may introduce a new type of annoyance which needs to be understood, just imagine aircraft flyovers more often like road vehicles.

5 Communication and dissemination

Below is a list of activities for communication and dissemination for NEFAT since the start the project from March 2023:

- On 6th December 2023, the study of noise assessment of RNP AR procedure designed from statistical wind for ESGG airport was presented at Centrum för Hållbar Luftfart (CSA) workshop.
- Conference paper “Noise from Flight Procedure Designed with Statistical Wind: Auralization and Psychoacoustic Evaluation EM Thoma, R Merino-Martínez, T Grönstedt, X Zhao” was presented at the 30th AIAA/CEAS Aeroacoustics Conference in Rome, Italy, June 2024.
- On 18th November 2024, the auralization and psychoacoustic evaluation of noise from flight procedure designed with statistical wind was presented at Swedish Aerospace Research Center (SARC) - Brazilian Aerospace Research Network (BARINet) aerospace workshop.
- On 10th December 2024, the study of wind impact on noise optimal procedures for ESSA Arlanda airport was presented at CSA workshop.
- Conference paper “Analysis of noise optimal approach procedures with on-site statistical meteorological effect EM Thoma and X Zhao” was presented at the Towards Sustainable Aviation Summit in Toulouse, France, Jan 2025.
- On 28th March 2025, a workshop was organized for sharing all the studies and results generated by NEFAT. Representatives from Transportstyrelsen, Swedavia, LFV, and Chalmers were invited and attended the workshop.

Furthermore, draft manuscript as described below is to be submitted to journals for publication consideration:

- A paper for the study as reported in section 3.3 Noise mapping for future aircraft fleet will be submitted to journal for publication consideration. In addition to the noise results as presented, based on the suggestion giving by the reference group member from Transportstyrelsen, an analytical method measuring the socio-economic cost for the transport sector as presented in (Trafikverket, 2024) will be implemented to deliver a comprehensive analysis.

6 Reference

- Åbom, M., Johansson, A., Bolin, K., & Basu, S. (2021). *Technical report for the KTH/Novair project Approach Noise Trails (ANT)*.
- Amadori, K., Jouannet, C., & Zhao, X. (2023). Towards Zero-Emission Transportation in Scandinavia. In *AIAA SCITECH 2023 Forum*. <https://doi.org/10.2514/6.2023-1909>
- Aures, W. (1985). Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale. *Acta Acustica united with Acustica*, 59(2), 130-141.
- Aviation Environmental Design Tool (AEDT) Version 3d*. (2021). U.S. Department of Transportation. https://aedt.faa.gov/3d_information.aspx
- Chandrasekaran, N., & Guha, A. (2012). Study of Prediction Methods for NOx Emission from Turbofan Engines. *Journal of Propulsion and Power*, 28(1), 170-180. <https://doi.org/10.2514/1.B34245>
- Daniel, P., & Weber, R. (1997). Psychoacoustical roughness: Implementation of an optimized model. *Acta Acustica united with Acustica*, 83(1), 113-123.
- Di, G.-Q., Chen, X.-W., Song, K., Zhou, B., & Pei, C.-M. (2016). Improvement of Zwicker's psychoacoustic annoyance model aiming at tonal noises. *Applied Acoustics*, 105, 164-170.
- Ekstrand, H., Petit, O., Wall, M., & Ziverts, U. (2022). *Förstudie – Buller relaterat till icke-raka inflygningar med variabla inflygningsvinklar – ett projekt inom IRIS programmet*.
- Eurocontrol. (2022). *EUROCONTROL Aviation Outlook 2050 Main Report*.
- Gray, J. S., Hwang, J. T., Martins, J. R., Moore, K. T., & Naylor, B. A. (2019). OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, 59(4), 1075-1104.
- Greco, G. F., Merino-Martínez, R., Osses, A., & Langer, S. C. (2023). SQAT: a MATLAB-based toolbox for quantitative sound quality analysis. *Inter-Noise and Noise-Con Congress and Conference Proceedings*,
- Grönstedt, T. (2000). *Development of methods for analysis and optimization of complex jet engine systems*. Chalmers Tekniska Högskola (Sweden).
- Grönstedt, T., Au, D., Kyprianidis, K., & Ogaji, S. (2009). Low-Pressure System Component Advancements and Its Influence on Future Turbofan Engine Emissions. *Turbo Expo: Power for Land, Sea, and Air*,
- HeartAerospace. (2025). *Introducing the ES-30 A clean-sheet hybrid-electric design engineered to reignite regional aviation*. Retrieved May 4 from <https://heartaerospace.com/es-30/>
- Doc 9905, Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual, (2021).
- International Organization for Standardization. (2017). ISO norm 532-1 – Acoustics – Method for calculating loudness – Zwicker method. In.
- Lautsch, M.-L., Ring, T. P., & Langer, S. C. (2024). *Validation of the Doc 29 best-practice prediction method of aircraft noise on the ground at a single flight level using ADS-B data* DAGA 2024, Hannover.
- LFV. (2024). *Aeronautical Information Publication ESSA Stockholm/Arlanda* <https://www.aro.lfv.se/Editorial/View/IAIP?folderId=55>
- Osses Vecchi, A., García León, R., & Kohlrausch, A. (2016). Modelling the sensation of fluctuation strength. *Proceedings of Meetings on Acoustics*,
- PACE Aerospace Engineering & Information Technology GmbH (2023). *PacelabEngineeringWorkbench: plEngineeringWorkbench 8.1. Recommended Method for Computing Noise Contours Around Airports, Doc 9911, 2nd Edition*. (2018).
- Report on Standard Method of Computing Noise Contours around Civil Airports, Doc 29, 4th Edition*. (2016).

- Schiavina M., F. S., Carioli A., MacManus K. . (2023). *GHS-POP R2023A - GHS population grid multitemporal (1975-2030)*. PID: <http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe>,
- Seitz, A., Habermann, A. L., Peter, F., Troeltsch, F., Castillo Pardo, A., Della Corte, B., van Sluis, M., Goraj, Z., Kowalski, M., Zhao, X., Grönstedt, T., Bijewitz, J., & Wortmann, G. (2021). Proof of Concept Study for Fuselage Boundary Layer Ingesting Propulsion. *Aerospace*, 8(1), 16. <https://www.mdpi.com/2226-4310/8/1/16>
- Swedavia. (2023). *Miljörapport 2023 Stockholm Arlanda Airport*.
- Thoma, E., Grönstedt, T., Otero Sola, E., & Zhao, X. (2023). Assessment of an Open-Source Aircraft Noise Prediction Model Using Approach Phase Measurements. *Journal of Aircraft*, 1-15.
- Thoma, E. M., Grönstedt, T., & Zhao, X. (2020). Quantifying the Environmental Design Trades for a State-of-the-Art Turbofan Engine. *Aerospace*, 7(10), 148. <https://www.mdpi.com/2226-4310/7/10/148>
- Thoma, E. M., Merino-Martinez, R., Grönstedt, T., & Zhao, X. (2024). Noise From Flight Procedure Designed With Statistical Wind: Auralization and Psychoacoustic Evaluation. In *30th AIAA/CEAS Aeroacoustics Conference (2024)*. <https://doi.org/10.2514/6.2024-3017>
- Trafikverket. (2024). *ASEK 8.0 Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn*
- Transportstyrelsen. (2024). *EntryScape Tabular Data API*. <https://transportstyrelsen.entryscape.net/rowstore/dataset/4742f5c5-e877-4baa-b45c-4e3ab39a629e/html>
- von Bismarck, G. (1974). Sharpness as an attribute of the timbre of steady sounds. *Acta Acustica united with Acustica*, 30(3), 159-172.
- Zhao, X., Ziverts, U., Ekstrand, H., Ullvetter, M., Lukic, P., Näs, A., Olsson, E., Ridal, M., Johansson, Å., & Wall, M. (2024). Curved flight procedure construction with site-specific statistical meteorological data: A Swedish example. *Journal of Air Transport Management*, 121, 102694.