National Aviation Academy

International Journal of Transportation Research and Technology
e-ISSN: 3079-6075
DOI: 10.71108/transporttech.vm02is02.03

TRANSPORT TECH JOURNAL

Research Article

Multi-Level Design Space for the Aircraft Exposure Assessment on Environment by Concerting Vehicle-Airport-Fleet Operational Scenarios

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Timescale of article

Received: 22 October 2025
Accepted: 08 December 2025
Published: 25 December 2025

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Keywords

Aircraft noise, Noise management, Reference aircraft, Reduction at source, Calculations, Measurements

Cite this article as:

Zaporozhets, O., Kazhan, K., Makarenko, V., Tokarev, V., Synylo, K. & Chyla, A. (2025). Multi-Level Design Space for the Aircraft Exposure Assessment on Environment by Concerting Vehicle-Airport-Fleet Operational Scenarios. *International Journal of Transportation Research and Technology*, 2(2), 38-54.
DOI: 10.71108/transporttech.vm02is02.03

Abstract

A multi-discipline design optimization approach is used by aircraft manufacturers to provide the necessary aircraft performances at conceptual design stage. The concept of the reference aircraft is fundamental to show the achievements in baseline aircraft design, their efficiency to solve the environmental problems. Aircraft noise (AN), engine emission and fuel consumption reduction at source by new technology implementation in aircraft design is a strategic element of the environment protection management in aviation sector, their stepwise development provides closer distances of the protection zone's boundaries between the runways/flight paths and residential areas in vicinity of the airport. In grounding the necessary noise reduction technology for baseline aircraft design its acoustic efficiency should be assessed for appropriate AN standard limits in accordance with ICAO certification procedures, for the single flight event at departure/arrival stages in airport, in overall airport traffic scenario and at least regionally/globally. All of them must show that AN exposure continues to be the not-growing and ICAO Balanced Approach is still feasible for effective AN exposure and impact management. For fuel burn and aircraft engine emission besides the certification requirements the net-zero CO_2 emission for the air traffic should be confirmed. The approach to coordinate the multi-factor exposure assessment at Vehicle-Airport-Fleet scenarios is presented and recommended for the usage in effective implementation of the reduction technologies in aircraft designs. The approach starts at new aircraft design stage, but it is fully connected with expected operational and maintenance performances influencing the exposure levels on environment.

1. Introduction

Designing a new aircraft is an optimization process that encompasses several disciplines that affect the aircraft's performance during operation and maintenance. The aviation industry needs a set of tools for multi-discipline design optimization (MDO) that would provide designers with the means to further improve the aircraft performance of already mature solutions (Park, 2007). The new aircraft design must show that its performances in operation and maintenance confirm airworthiness standards and/or specifications like (EASA, 2023), including the environmental factors (EASA, 2025; ICAO, 2019a). The environmental impact is an aspect which is increasingly being considered in the development of aerial vehicle applications (Papageorgiou et al., 2018), including aircraft noise (AN) (EASA, 2021).

For the past two decades, ACARE - as an Advisory Council for Aviation Research and innovation in Europe - has been addressing strategic policy issues in the European aviation sector based on open discussion and transparent consensus in decision-making, especially in the areas of safety and environmental protection. The EU Green Deal Directive has introduced radically new priorities for the whole EU transportation sector (European Commission, 2021). According to the latest ACARE policy paper (ACARE, 2022), by 2050, 75% of the European regional and short- and medium-range (SMR) aircraft fleet will consist of new aircraft, which are due to enter service from 2035, largely aimed at addressing greenhouse gas (GHG), mainly CO_2, emissions in the aviation sector.

In short- and mid- terms, mainly till the 2035, the contribution to EU FIT-55% program must be provided comparing with the reference year 1990, when the air traffic was much less but fuel consumption and engine emission by aircraft were quite big. The ICAO requirements to aircraft fuel burn and CO_2 emission were absent during that period, like the newish standard limits for the local air quality (LAQ), especially the new limits for the particles (PM) defined by (ICAO, 2019a) for their number and mass. The latest CAEP/13 meeting adopted the new limits for the fuel burn and CO_2 emission, which is 10% stricter compared with the previous. Because of joint stringency investigation of fuel burn/CO_2 emission and noise was implemented the new limits for aircraft noise have been adopted with higher priority for fuel burn and less for the noise performances of the new aircraft, which must start to operate after 2029 (ICAO, 2025).

Regarding aircraft noise (AN) by ACARE vision in 2050, aircraft should deliver a 65% reduction in perceived noise emissions per operation compared to a 2000 reference aircraft – this should be achieved through noise reduction technologies (NRT) in aircraft design, air traffic management (ATM) improvements and operational noise abatement procedures (NAP). As a medium-term goal (by 2035), 'Fly the green deal' (ACARE, 2022) considers the possibility of no population increase within the Lnight=50 dB contour relative to 2019 baseline, as well as no existing population within the Lnight=50 dB contour without noise reduction measures, as well as no population increase within the LDEN=65 dB contour, as well as no existing population within the LDEN=65 dB contour without noise reduction measures.

Thus, the ACARE goals are defined as for the aircraft design and its operational performances directy, so as for the airport exposure by noise on the community. Main accent in short- and mid- term period is done on land use management principles (ACARE, 2022), applied for each airport region in Europe – regional or hub, especially if these airports are with eliminated by noise capacity. In this case, even non-acoustic factors, their role through communication and community involvement, play radically important aspects of the impact of noise on humans, influencing the stability or even reduction of the proportion of the population irritated by noise (Graeme et al., 2020). Such a compromise solution is clear if to take in mind the latest results of the IPCC scientific reports and Long-Term Aspirational Goal (LTAG) of the ICAO to support the elimination of the atmosphere temperature rise not higher than 1.5 degrees. These IPCC and ICAO priorities are the basis for European regional directives and programs, so as for the aviation sectorial program Clean Aviation (Clean Aviation, 2024).

Today the AN exposure around the airports is accurately defined by calculation (ICAO, 2018) for the current and future air traffic scenarios (Fleming et al., 2022) and by noise monitoring directly in situ (Asensio et al., 2012). In principle, calculations and measurements complement each other (Zaporozhets, 2025), solving its own specific problems (Zaporozhets et al., 2011), but their synergy in airport management can significantly increase the effectiveness of noise exposure reduction, and accordingly more effectively regulate its exposure and impact, especially in noise-sensitive areas. The assessment of the AN exposure of current and future air traffic scenarios requires fleet-level studies also where variables such as air traffic trend, fleet composition, available noise reduction technology options, and rate of penetration of novel aircraft into the scenario are considered (Fleming et al., 2011). So, the multi-level assessment of the new aircraft designs or of any NRT is looking obligatory procedure today (Delfs et al., 2018) before their implementation into practice.

The EU EFACA project shoud elaborate TRL3 demonstrations of technologies relevant to the greening of aviation (Dmytriyev et al., 2025) and preliminary designs of regional hybrid-electric (Fil et al., 2025a) and liquid hydrogen fuelled (Fil et al., 2025b) aircraft. Priorities in their designs are predefined by current global ICAO (ICAO, 2025) and regional EU policies (European Commission, 2021). The noise performances are considered as interfering with GHG and LAQ emission of the aircraft, somewhere being in trade-off compromise with them, like it was during the dual standard setting to noise and CO_2 aircraft emission. Such dual standard setting process requires deep coordination across involved working groups to guide the technical steps of this integrated standard setting process along the compromise solution between the priorities. A specific system approach and calculation platform are designed within the EFACA project to look on and solve the interfering priorities at three shown above levels of aircraft noise assessment – single aircraft flight event, airport traffic and fleet traffic scenarios.

2. AN assessment and management – a multi-level approach

Reducing the negative impacts on communities of the environmental noise exposure is one of the key objectives under the EU's zero pollution action plan (European Environment Agency, 2022). It aims to reduce the number of people chronically disturbed in Europe by noise from transport (by 30% by 2030 compared with 2017), which depends directly on the number of exposed people to noise – a metric normally used to estimate noise exposure inside the communities together with areas of noise contours of significant level (for example, 55dB L_{DEN}). Fig. 1 shows an example of noise contours for an airport (one of the main regional airports in Poland, where air traffic is growing faster than the EU average), which are used also for the definition of AN zones (ANZ) to eliminate its exposure on population. The L_{DEN} index (Fig. 1(a)) and night equivalent noise level L_{Night} (Fig. 1(b)) contours for current and forecasted traffic scenarios are compared with the ANZ boundaries (shown separately for this airport in Fig. 2), adopted at the legislative level (Sejmik Województwa Pomorskiego, 2016) for the airport under consideration to show and manage the compatibility of the airport (aircraft fleet and traffic) with nearby communities, defined by the AN protection requirements.

a) b)

Fig. 1. Calculated AN L_{DEN} (a) and L_{Night} (b) contours for current airport scenario, compared with the ANZ boundaries (Source: Authors' own work)

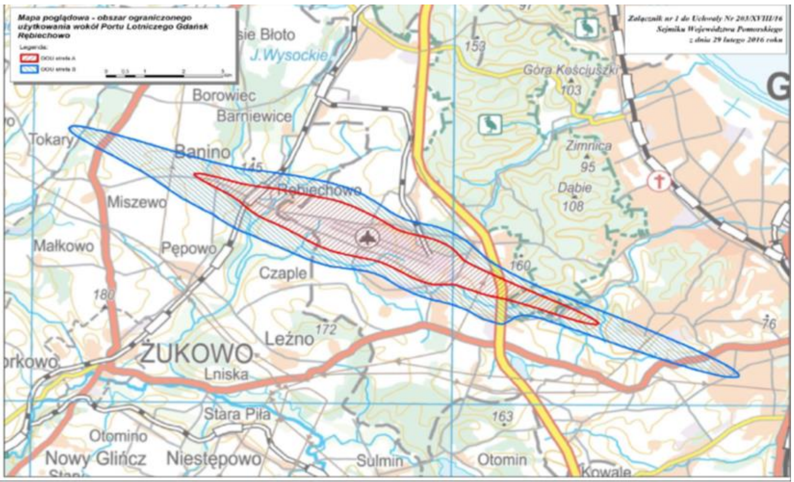


Fig. 2. AN zones' boundaries for the population protection from noise exposure adopted by legislation (Sejmik Województwa Pomorskiego, 2016)

Projections of population growth and transport activity, including the aviation, are (or should be) considered in combination with implementation of the protection measures in all expected scenarios within EU boundaries, including optimistic for aviation sector. Among them, the implementation of the new quiet and less energy consuming aircraft is considered as a main instrument to contribute to achieving the mid-term European goal (European Environment Agency, 2022) by decreasing the number of exposed and annoyed population by up to 70%. The ICAO uses similar approach for AN exposure assessment – noise contour LDN = 55dBA areas and number of people inside them – to show the relevance of the AN problem and assess the coping capacity of the measures – including standard requirements – trying to manage it. During last two decades the effectiveness of the ICAO efforts, realized through the Balanced Approach (BA) to AN management (ICAO, 2008), allows to stable the values of both metrics: total aircraft noise contour 55 DNL area worldwide is close to 15000 km² at the moment (it was 14400 km² in 2015 and 15200 km² in 2024), exposed number of people is ~30 mln. people (Fleming et al., 2022). The effect depends mostly on new quiet aircraft contribution to the fleet – in USA from 2000 to 2023, AN exposure was reduced by 55 % and stabilized (Fig. 3) while air traffic rose by 33 %. The main contribution to the reduction of AN impact was made in 1998-2002, when the ICAO decision to withdraw aircraft complying with Chapter 2 of Annex 16 was implemented. A similar reduction in AN impact was observed in 2019-2022 due to the reduction in air traffic related to COVID, which returned to pre-crisis levels in 2025.

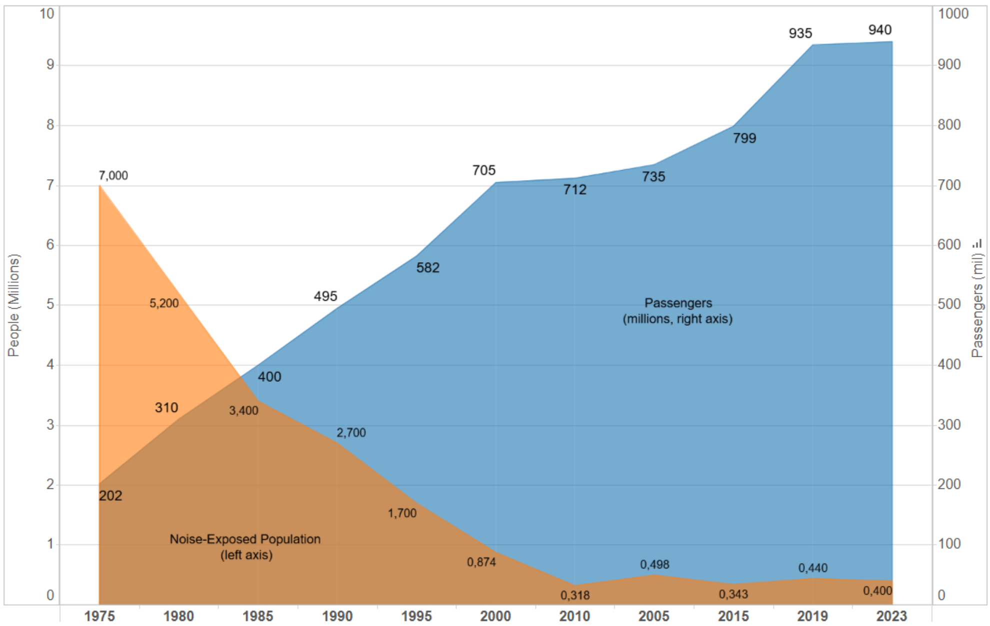


Fig. 3. AN exposure in the USA in comparison with air traffic rise (Airlines for America, 2024)

Looking on the reference aircraft with 2000 technology in its design the Airbus-320ceo is mostly appropriate for SMR flights and 65% of the noise emission reduction means 15 EPNdB reduction of its certification noise level at each point of noise control (ICAO, 2019a). In 2000 the Airbus-320ceo noise was assessed as -5.0 EPNdB to ICAO Chapter 4 cumulative noise limit, further generation aircraft Airbus-320neo achieved -16.0 EPNdB to ICAO Chapter 14 cumulative noise limit (ICAO, 2019b). The Noise-Power-Distance (NPD) data for the A-320 family in ANP data base are changed appropriately, showing the expected decrease of the noise footprint (Fig. 4) for the SMR aircraft more than twice (EASA, 2025): 27 km2 in 2025 (state-of-the-art aircraft design correspondent with adopted in February 2025 new ICAO Chapter 16) via 61 km2 in 2005 (ICAO Chapter 4 aircraft design).

The strategic importance of new quieter aircraft implementation in the operating fleet and air traffic directed by ICAO standard requirements (ICAO, 2019a) is grounded by ICAO/CAEP globally to ensure its feasibility and effectiveness at any airport worldwide (Fleming et al., 2022). A Balanced Approach to AN management at airports (ICAO, 2008) stands on 4 pillars, its effectiveness begins with the ability of the sector to reduce the exposure and impact of aircraft noise by introducing more silent aircraft first of all. This is the main successful driver (without risen AN exposure) of air traffic growth in the future due to the growing demand for air travel. Appropriate noise limits for human activities near airports are determined by the sensitivity of the latter to noise (WHO, 2018) and the compatibility of airport traffic with developing communities around airports (US FAA, 1984). Problems of inappropriate AN exposure and impact on environment are the results of inconsistent solutions in airports, depending mostly on misunderstandings of the subjects that influence the over-limits of the ICAO standard requirements at specific points of noise control in airport surroundings.

ICAO noise limits are the technical requirements to the aircraft, they are defined at specific locations of the departure and arrival flight paths (Fig. 4), which should be realized with specific requirements to flight procedures and environmental (sound propagation) conditions (ICAO, 2019a). Noise measurement conditions during certification tests are also different from AN monitoring in airports (Asensio et al., 2012) in many aspects – emphasizing the misunderstanding between certification and operation measured noise levels. The certification requirements at the sideline and flyover measuring points (Fig. 4) have to be performed for the maximum take-off mass (MTOM) while the operational aircraft mass is usually less, it depends on distance of flight to destination point.

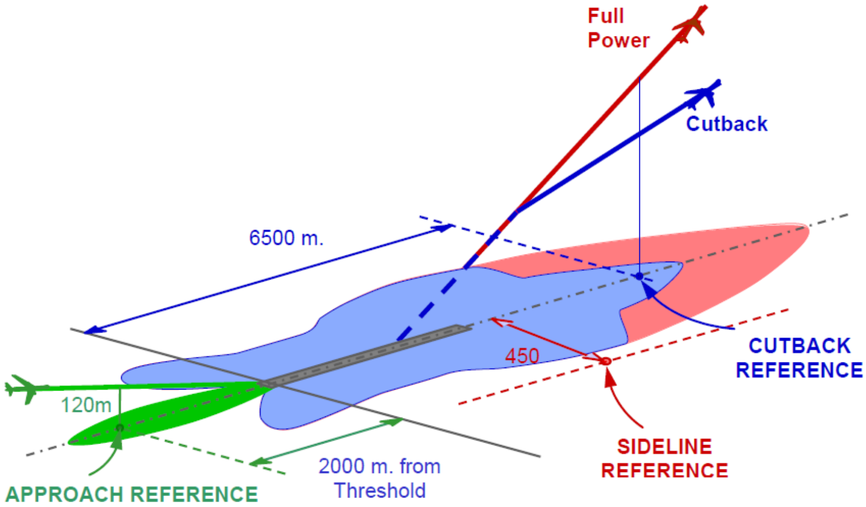


Fig. 4. Aircraft noise footprint and ICAO certification points for departure and arrival (modified from the (ICAO, 2019a))

The certification for the sideline measuring point has to be performed for full take-off thrust and the reduced thrust (engine cut-off) for the flyover point to the value providing the safe climbing of the aircraft during departure (ICAO, 2019a), which is much different from normal climbing procedure in usual operation. For example, for the two-engine aircraft safe climbing gradient should be not less than 3% and flight velocity – not less than V2+20 km/hour, where V2 is a safe velocity for the aerodynamic configuration of the aircraft at take-off, they both provide maximum possible engine cut-off during certification trials and minimum noise level at flyover measurement point. In operational conditions the variation of the aerodynamic configuration (high-lift devices of the wing), flight velocity and operational modes of the engine within the safety limitations is quite big and may differ significantly from the certification. Thus, the comparisons of the monitored noise levels with measured at certification trials must calculate the differences due to these differences, so as the differences changes of monitoring locations relatively the certification points.

Implementing the ICAO methodology, existing AN calculation tools (Zaporozhets & Levchenko, 2021) can fairly accurately estimate the distribution of AN exposure around flight paths, which is required to confirm the ANZ boundaries around the airport, first of all. The current methodology is recommended for equivalent noise levels (ICAO, 2018), which dependent of duration of their equivalence and correlated better with human annoyance by noise (WHO, 2018), and less appropriate for temporally varied noise levels at any specific point of interest because of equivalence averaging of their values. Using a statistical classification process, the commercial aircraft fleet is reduced to four representative-in-class aircraft (Torija & Self, 2018) on the basis of aircraft design and flight performances, noise and engine exhaust emissions. They are also selected to be used as baseline cases for the high-level assessment of the environmental benefit of novel aircraft technologies, in particular specific NRT. With relatively minor decrease in accuracy of noise assessment for the traffic scenario (<5%) a reduction of computational time is achieved essentially when the whole aircraft fleet is replaced with the four representative aircraft – the approach is used by expert analysis in CAEP (ICAO, 2019b).

The equivalent noise levels like L_{Aeq} or combined of them noise indexes L_{DEN}, used for the strategic impact assessment (Torija et al., 2018), definition of ANZ boundaries and community annoyance/impact assessment, are different from sound exposure levels SEL or EPNL by a number of flight event n contributing to air traffic in airport flight scenario and duration T of their equivalence:

$$L_{Aeq} = SEL - 10 \lg T + 10 \lg n \quad (1)$$

where T is a temporal interval in seconds to which L_{Aeq} or L_{DEN} should be assessed (duration of the equivalence), n – number of single events with sound exposure level SEL. All the levels are defined in dBA except the EPNL, EPNdB. Sound exposure of single flight noise event depends on location and conditions of exposure determination. Here in formula (1) the value of SEL is defined for determining type of the aircraft in scenario under consideration, its flight and engine operation modes. The equivalent level L_{Aeq} is simply a summa of all single event exposures averaged by duration of their supervising at the point of consideration, sometimes including the penalty if supervision (during the equivalence duration) covers the sensitive to noise period of the day like a penalty 10 dBA is given to events that occur during the night time.

AN levels EPNL, measured or calculated during the certification procedures, represent only the point-located noise exposure from the aircraft during the departure and arrival – a noise footprint for the landing-take off (LTO) is a better metric to describe the AN exposure of any aircraft type in total or by flight stage. The EPNL and SEL at certification points correlate well with noise footprints (contours), so if the effect was shown by certification trials the correspondent effect should be expected for the AN footprint. An analytical basis for a trade-off relationship between certification noise levels EPNL and noise contour areas for departure and arrival operations was developed in (Powell, 2003). In (Zaporozhets et al., 2011) this approach was expanded to wider operational conditions than defined by certification procedures to show better correspondence between the certified levels and noise footprints in usual aircraft operation. In (Zaporozhets et al., 2022) it was described how expand the approach to airport noise scenario (footprint) assessment: based on LTO exposure level footprint to define the airport noise footprint bounded by L_{AEq} or L_{DEN} indices. With quieter determining aircraft in a fleet of the scenario under consideration the dominance of the single flight noise exposure contour may not be diminished by noise equivalent contour. The following strengthening of noise requirements for the aircraft in design may provide the conditions of disappearing the single event AN contours (footprints) with sufficient for analysis and management levels (L_{Amax} = 75 dBA for the night and 85 dBA for the day periods), as they are used in Fig. 4 in (Zaporozhets et al., 2022) from consideration in tasks of population exposure by noise.

The ICAO strategic goal in aircraft noise management is formulated globally – to eliminate number of people exposed to AN worldwide – at fleet level. This goal is mostly achieved at current level by two elements of the ICAO BA – AN certification and AN zoning. Other two BA elements are used locally in airports to solve the particular tasks in their vicinity, where the AN levels may violate the limits and eliminate airport operational capacity. A significant reduction in noise emissions at the source and the creation of relatively quiet aircraft have led to the approach of noise contours with levels equal to the established limits for public health protection to the borders of the airport territory. In turn, this allows to bring the activities of the population, including their residence, closer to the airport. But the requirements for determining noise contours and corresponding zones remain unchanged, computational methods are still decisive for them.

3. VALDES simulation platform

Among the basic requirements for the design of new aircraft, in particular the Top Level Aircraft Requirements (TLAR), it is mandatory to comply with the EPNL limits defined by the relevant chapter of Volume 1 of ICAO Annex 16 and the MTOM of the aircraft (ICAO, 2019a). Aircraft Design & Flight Performance Platform (ADFPP) was developed (Fig. 5) as a core element of the wider calculation platform VALDES (Fig. 6) - **V**ehicle-**A**irport-f**L**eet **DES**ign platform - to realize complex environmental assessment and multi-disciplinary optimization (MDO) necessary during the new aircraft design. It must show that new baseline aircraft performances in operation and maintenance confirms airworthiness standards (or certification specifications like (EASA, 2023)) including the environmental factors (EASA, 2025) with AN assessment among them (EASA, 2021), for example, by means of NoiTra and IsoBella calculation tools (Zaporozhets & Tokarev, 1998a; Zaporozhets et al., 2011).

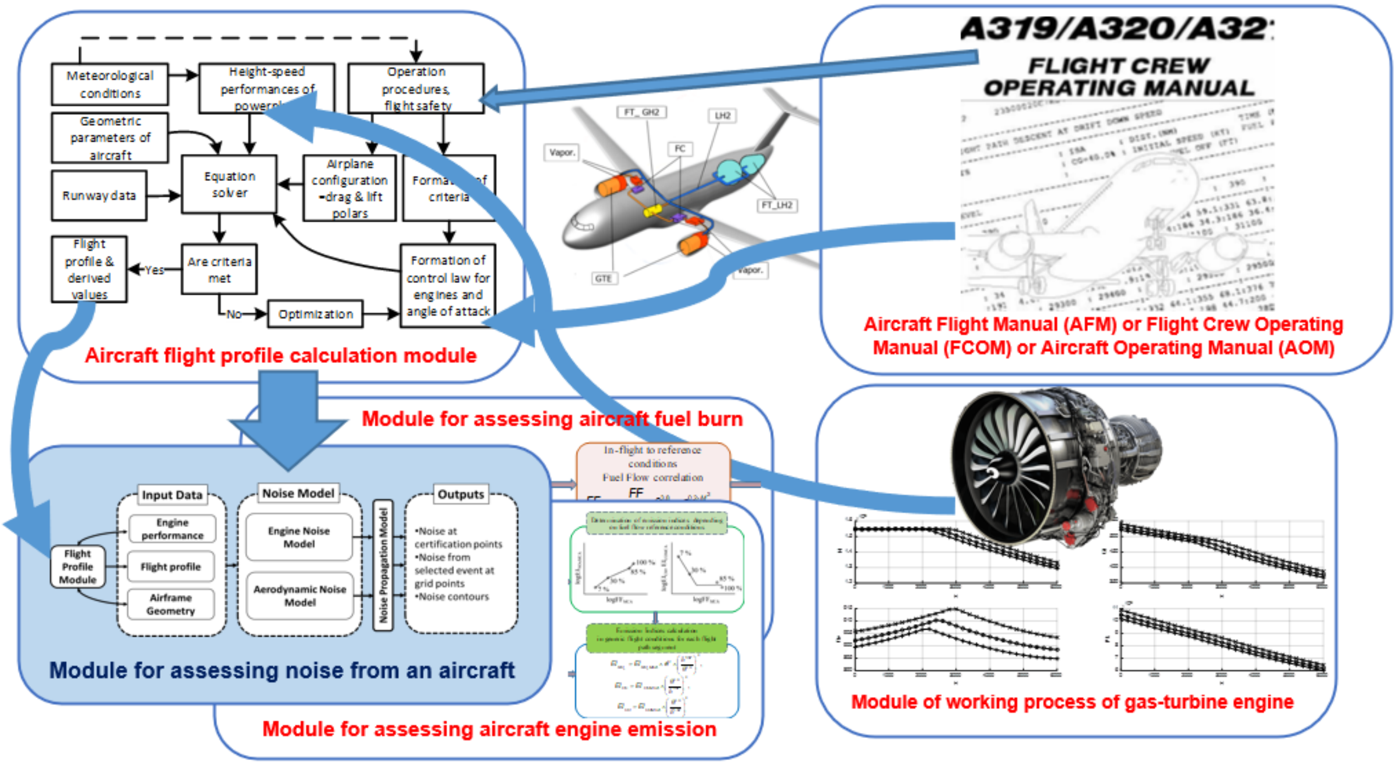


Fig. 5. ADFPP - Aircraft Design & Flight Performance Platform for the complex environmental assessment and multi-disciplinary optimization during the new aircraft design (Source: Authors' own work)

The ADFPP determines aircraft design and flight parameters (Fig. 5) for both baseline and reference aircraft by analyzing their models for aircraft flight and engine operation. In particular, for the liquid hydrogen fuelled aircraft (Fil et al., 2025b) the reference aircraft Airbus-320neo (A320N) was proved. Thus, for modeling the reference aircraft in operation due to TLAR all available technical documents for the A320N and its engine LEAP were used. The core of this approach is the following modules: a module for calculating the working process of gas turbine engines (operation performances of the engine - OpEn module), an in-flight profile calculation module (module New Flight), and the modules for calculating the parameters of environmental exposure defined by the aircraft in flight. An OpEn module realizes the algorithms described in (Yakushenko et al., 2014), a module NewFlight solves flight dynamics equations using convenient interface usually dividing a full flight path on several segments (Makarenko et al., 2024; Synylo et al., 2024).

Flight segments refer to specific portions of the aircraft flight, each with its own unique set of operation procedures (Makarenko et al., 2024). They are predefined by flight safety requirements and accuracy of flight performances. OpEn module calculates the engine operational performances for every flight stage in accordance with required flight parameters. They are quite detailed to engine components – fans, compressors, combustion chamber, turbines and core and bypass exhausts – their air flows, temperatures and pressures are necessary for accurate engine noise, as well for the emission and fuel burn assessment. And the engine thrust and specific fuel burn, which are the inputs for the NewFlight module at every stage of the fight profile.

Currently, the ISA conditions or ISA+10°C – as required by certification standards (ICAO, 2019a) – are considered in OpEn modelling but with availability of the necessary data (for correct OpEn and NewFlight calculations along the TLAR flight conditions) for other meteorological conditions the calculations and analysis are also possible. Because of the highest priority of fuel burn inside the set of environmental factors considered in MDO of new aircraft design a system of equations of aircraft flight is widened by inclusion an equation aircraft flight mass change due to fuel consumption, which is necessary for correct analysis of the aircraft flight profiles due to their TLAR. Thus the ADFPP is similar to aircraft design and flight performances platforms like PRADO/PANAM (Bertsch et al., 2010; Bertsch et al., 2025), FLIGHT (Filippone, 2017), ANOPP2 (Berton et al., 2020) and ASTRID-H (Piccirillo et al., 2022).

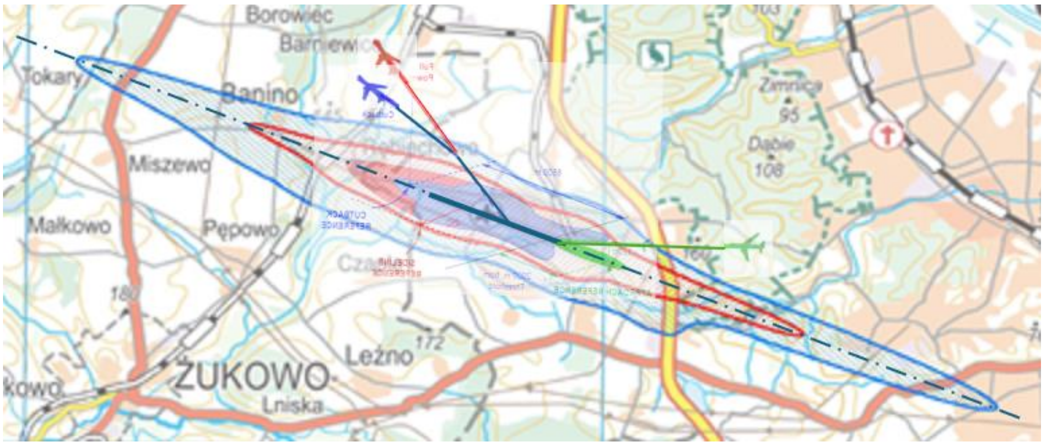


Fig. 6. Modular approach to evaluation of noise, fuel burn and engine emission metrics by ADFPP: combined example for AN exposure assessment is shown by comparison of noise certification, footprint (both shown in Fig. 4) and airport scenario (Fig. 2) platforms (Source: Authors' own work)

Determining a reference (best analogue of the aircraft being designed) aircraft for a new baseline (designed) aircraft allows starting the design process with an existing set of analogue data and to step-by-step compare the required flight characteristics and environmental exposure metrics between the reference and baseline aircraft to show the improved efficiency of the latter compared to the characteristics of the reference aircraft. The novel configuration should not only provide the capability to increase performances and to be economically viable but also reduce fuel consumption, engine emissions and noise essentially to reach the long-term aspirational environmental goals in future (ACARE, 2011). For better understanding of the comparison between the baseline and reference acoustic models the clear difference should be defined between the specific acoustic sources in their aircraft/engine design and how new NRT should be implemented to determine them and make the novel designs quieter. ADFPP provides an iterative process in novel aircraft designing and the design loop should be repeated until the design converges, including that its environmental exposure metrics will be in accordance with required ICAO standard limits.

Platform VALDES (Table 1 and Fig. 6) provides the multi-level assessment and analysis of the environmental exposure and impact of the reference and baseline aircraft to understand the influence of any improvements in their design (or retrofits), operation and maintenance by comparisons with their initial scenarios. Number and scale of the scenarios are dependent of goals of the assessment – if they are defined by strategic values (ICAO, 2022; ACARE, 2011) the scenario scale should be the global aviation system level. The aircraft in its original configuration – the reference aircraft configuration – should be assessed and/or measured in LTO noise trials to describe the initial data set necessary for comparison analysis with baseline concept of new aircraft (Bertsch et al., 2025). The certification flight procedures necessary for the AN exposure evaluation or for the engine emission during the LTO stages of flight are the unified data set for such purposes (Bertsch, 2013; ICAO, 2019a). New conceptual aircraft is usually designed to achieve the far-reaching strategic objectives – currently in Europe defined by the ACARE Strategic Vision (ACARE, 2022), which cannot be accomplished by application of the retrofitting NRT at the level of aircraft components only (Delfs et al., 2018). Their airport (local) and fleet level (global) assessments on a platform of adequate scenario should be provided and platform VALDES serves these purposes.

Table 1. VALDES platform levels of AN assessment and management

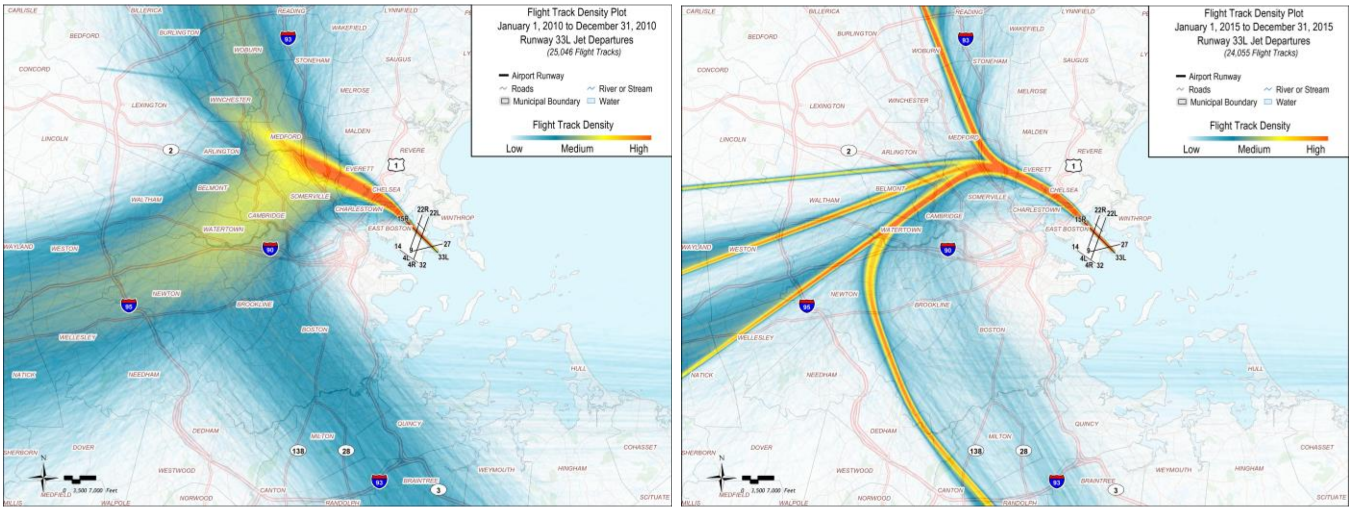
Level	Content	Requirements or recommendations for assessment	Requirements or recommendations for management
0	AN levels at certification points, Fig. 4	ICAO Annex 16, 2019, ICAO Doc 9501, 2018	ICAO Annex 16, 2019, ICAO Doc 9501, 2018
1	LTO AN footprint, Fig. 4	ICAO Doc 10127, 2019	ICAO LTAG, 2022; ACARE, Fly the green deal, 2022
2	Airport noise footprint, Fig. 6	ICAO Doc 9911, 2018	ICAO Doc 9184, 2018
3	Aircraft fleet noise footprint, Fig. 6	ICAO Doc 10127, 2019	ICAO LTAG, 2022; ACARE, Fly the green deal, 2022

AN compatibility of any airport may be considered as broken if the ANZ are defined only by calculation of flight AN exposure, and their measurement results are definitely higher at their borders. If the ANZ distances from the runway axis are smaller due to quieter aircraft implemented in operation such situation is looking obvious, so the calculations of AN contours, which are used for ANZ border defining, should be confirmed by AN level measurements. Accuracy of AN measurements and calculations must be equalized where this is possible in practice because of their simultaneous importance and even synergy effect on accuracy, reliability and efficiency of the AN zoning as an element of ICAO balance approach to AN management in airport. Of course, the data are compared for the same conditions of generation and propagation of AN. If the calculations are performed for ISA conditions, but the measurements are not, then the measurement results should be given under the conditions of the calculations or vice versa.

4. Discussion of AN exposure assessment at certification and airport scenario conditions

The certification levels EPNL are defined for quite specific conditions – flight mass must be MTOM for the aircraft type, atmospheric conditions are equal to ISA at sea level and the temperature 25℃ (ISA+10℃). Their fundamental differences from normal operating conditions are the following: the difference in the values of meteorological parameters both at the level of the ground surface - the runway surface, and at the height of the atmosphere; the difference in the take-off mass from the maximum MTOM, which is mandatory for the conditions of the ICAO standard; the difference in the flight parameters - aerodynamic configuration, flight speed and engine operating mode from the recommended values of the certification procedures. Also, an important element is the so-called piloting culture and the influence of meteorological phenomena, which cause unexpected changes in flight parameters, especially flight speed and engine operating mode, and which may be at the level of flight safety limits.

The noise exposure from each take-off or landing of an aircraft is significantly affected by the presence of so-called corridors at the airport, installed by ATM rules along nominal routes in order to prevent noise exposure above the established limits over the territory of settlements under the flight paths (Fig. 7(a)). Today, the implementation of the principles of performance-based navigation (PBN) allows for maximum localization of noise exposure along nominal routes and corridors limited by boundaries (Fig. 7(b)). PBN can optimize aircraft routes and ATM for a more efficient and sustainable air transportation by permitting aircraft operation on any desired flight path within the coverage of 'ground or space-based navigation aids (GNSS) or within the limits of the capability of self-contained aids, or a combination of these' as predefined by RNAV (Area Navigation) concept (ICAO, 2013a). The PBN can be used for every phase of flight to achieve the sustainability benefits by reducing lateral and vertical clearance within the flight corridors' limits, in particular reducing the noise exposure over the residential areas, for example by implementing the principles of Continuous Climb (ICAO, 2013b) and Descend (ICAO, 2010) Operations.



a) b)

Fig. 7. AN exposure in the vicinity of the Boston airport without (a) and with (b) PBN rules implemented in ATM (Salgueiro et al., 2021)

An approach for significantly reducing the combinatorial nature of fleet-level studies, and for enabling more flexibility to analyze aviation scenarios with multiple technology, operational and ATM options is to reduce the aircraft fleet to a number of representative aircraft categories (Torija & Self, 2017), which is similar with approach used by Independent Expert panel (IEP) in CAEP for the analysis of new available NRT in aviation sector (ICAO, 2019b). In case of AN exposure assessment, the modelling tools due to recommendations of (ICAO, 2018) are highly sensitive to the number of aircraft types in the flight scenario. If the whole aircraft fleet is replaced with the four representative-in-class aircraft for computing AN contours a computational time may be reduced on ~80% with relatively minor decrease in accuracy +5% (Torija et al., 2017). A significant number of airports, particularly single-runway regional airports, have a reduced volume of operations carried out by short-medium-range (SRM) aircraft, such as the Airbus-A320 and/or Boeing-737 families – they dominate the fleet in the scenario and accordingly dominate the AN exposure.

For example, in Gatwick airport the 70% of aircraft flights in 2015 were made by Boeing 737-800. As shown in (Torija & Self, 2017), by selecting the Boeing 737-800 as a representative-in-class aircraft, the relative error of about 5% was observed in airport scenario noise assessment. Using the representative vehicles approach the more robustness demonstrated then for the computation of noise outputs in the set of 94 US airports evaluated due to the better performance of the representative vehicles approach in airports with a low volume of operations. The representative-in-class approach achieved similar high accuracy in evaluating the AN contours even for Heathrow airport scenario (Torija et al., 2017) with all operations more evenly distributed across the 4 aircraft categories: CRJ-900, A321-232, 747-8 and A330-343. All of them are used by ICAO/CAEP IEP for the for AN technology study (ICAO, 2019b), which are necessary for the ICAO standard limits proving procedures by analysis of the forecasted fleet-level noise exposure.

The same approach is realized inside the VALDES platform. The reference aircraft type used for the stepwise improvement by implementing the new NRT in design and achieving the design and flight performances of the baseline aircraft should be used as representative aircraft for the airport and fleet scenarios to show their efficiency at all three levels of the assessment. The layout of the virtual airport at the VALDES platform is used from a real case of a regional airport based on an analysis of the fleet, air traffic and other operational conditions, including flight routes and the effect of the wind rose on the annual distribution of flights between routes, and even the AN zonning principles (first of all their boundaries as shown in Fig. 1 and 2) to be included in overall noise management analysis similar to ICAO BA management. AN exposure analysis in the course of baseline aircraft enables an early identification of dominant acoustical sources in its conceptual design and promising NRT proving the low-noise configuration within given limits and boundaries (Bertsch et al., 2010). AN levels are predicted at separate points around the flight path with semi-empirical parametric noise source models (Zaporozhets & Tokarev, 1998a). Their formulations together with sound propagation effect models enable prediction of the various effects on noise radiation and propagation caused by the variations of aircraft aerodynamic configuration, engine operation, flight velocities and other operating conditions throughout simulated flight operations (Zaporozhets et al., 2011). Such analysis provided the possibilities to define the efficient low-noise flight procedures in any airport scenario, which are essential components of airport noise management programs (Zaporozhets & Tokarev, 1998b). For the reference aircraft the measured AN levels are essential support of its correct noise simulation (Bertsch et al., 2010), which are better compared with calculated levels if the flight path parameters are also supervised in measurements and transferred to calculation scheme with all necessary details of the operating procedure accurately (Zaporozhets et al., 2023, Chyla et al., 2023). Such reference AN model validation is a fundament for baseline AN study accuracy because the uncertainty of calculated results should accompany the modelled EPNL values like for AN certification trials.

Similar AN measurements were conducted for the EU EFACA project in regional Polish airports by means of AN monitoring systems (ANOMS), where the reference aircraft types are operated with essential contribution to traffic and noise exposure (Kazhan et al., 2025). Measurements by ANOMS are different from the AN certification requirement (ICAO, 2019a), their correct comparison with calculation must include the normalization of the measured data with calculated (or wise-versa). The normalization must include the atmosphere and topographical conditions influence, height over the ground surface and location to flight path of the microphone, flight procedure details – which are strictly defined in certification and widely varied in real operation.

The Airbus-320neo are operated in Polish airports, their noise and flight performances are supervised by ANOMS (Table 2, Fig. 8) including flight performances and analyzed for EFACA purposes, their corrected flight performances data are used for NoiTra, IsoBella, INM and AEDT calculations of noise exposure in EFACAport.

Reference aircraft noise exposure model for the novel EFACA hydrogen fueled aircraft – Airbus-320neo powered by CFM LEAP engines – is described in (Michel, 2013). Flight events from the RWY29 for A320N departure noise analysis were measured at NMT 2 (Sosnowa) with averaged sound levels: SEL=81,8 dBA; L_{AMAX} = 74,7 dBA. Flight Noise Test Campaign on A320 was done at Moron Spain, Airforce base in 2004 under the umbrella of the EU project SILENCE(R) (Malbéqui, 2018). Engine noise (Jet & Fan) were found predominant at aircraft take-off, baseline intake (Fig. 9): aircraft speed close to 150 kt; engine power settings between 75 to 95 %; slat / flap deflection at 18°/10°; Landing Gear was in Up position. Their spectra for arrival and departure noise are very similar with measured in Gdansk airport at the NMT 2 as shown in Fig. 9. The calculated spectra are also very close to the measured in certification trials and in operation - they confirm the adequacy and accuracy of the A320N noise model during LTO flight stages. Also the calculated AN levels for the certification conditions are compared well with measured data in trials – AN model for the Airbus-320neo is correct to be reference model for the new baseline LH_2-fueld design.

For the arrival noise the contribution from the dominant acoustic sources is shown – engine fan and wing slats and flaps. To reduce the overall aircraft noise means to implement noise reduction technologies (NRT) to these sources at first stage. These NRT are different, very specific to noise source. For example, the acoustic liners are used for the engine fan noise control, for both tonal and broadband components. For the wing slats and flaps noise the specific NRT exists also, but they may influence the aerodynamic performances of the wing at departure and arrivals, again a compromise solution is needed.

Table 2. Certified and calculated EPNL for A320NEO and Hydrogen at certification points

Aircraft name	Profile	Lateral	Flyover	Approach
EASA Data for A320-271N / PW1127G-JM		92-92.4	79.7-80	86.4-86.9
A320-271N	CONV	91.72	80.93	88.25
A320-271N	HYDRO	92.02	84.35	88.81
A320-271N_NDPs	UCON	89.75	77.94	85.05
A320-271N_NDPs	HYDRO	90.05	81.36	85.31

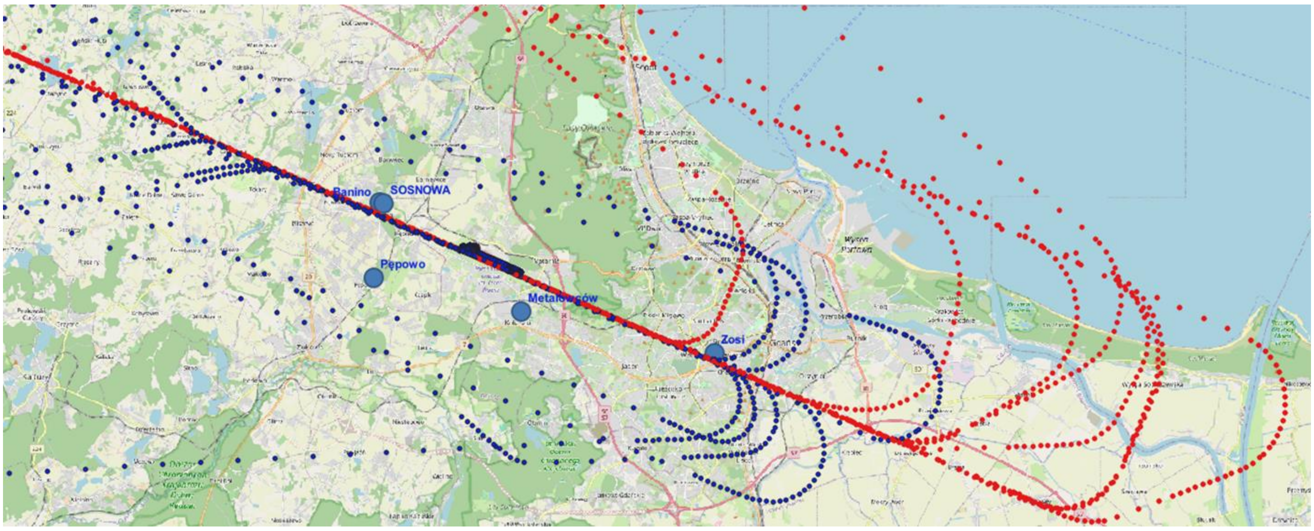


Fig. 8. Measured flight tracks of the arrivals (red) and departures (blue) in Gdansk airport for AN monitoring purposes: point Sosnowa is correspondent with NMT 2 location (Source: Authors' own work)

The NPD data of this aircraft is provided by ANP Data base from EASA for both approach and departure modes, for SEL and EPNL noise metrics used in LTO noise footprint and airport/fleet scenario assessment. Spectral analysis of the measured data at monitoring terminals and certification flight tests confirms the dominant contribution of engine fan and airframe (landing gear and wing high-lift devices) at departure (Fig. 9) flight stages.

Further noise reduction of the aircraft propulsion noise is expected to reach with UltraFan technology from Rolls-Royce (Rolls-Royce Press Release, 2023) within the EU Clean Aviation UNIFIED project (Flight Test Demonstrator). The expected environmental objectives of the Rolls-Royce UHBR turbofans are the following: ~10% fuel efficiency improvement demonstrated in comparison to 2020 state-of-the-art engines; ~40% reduction of NO_x; ~30% (or ~5 EPNdB at departure certification point) reduction of noise.

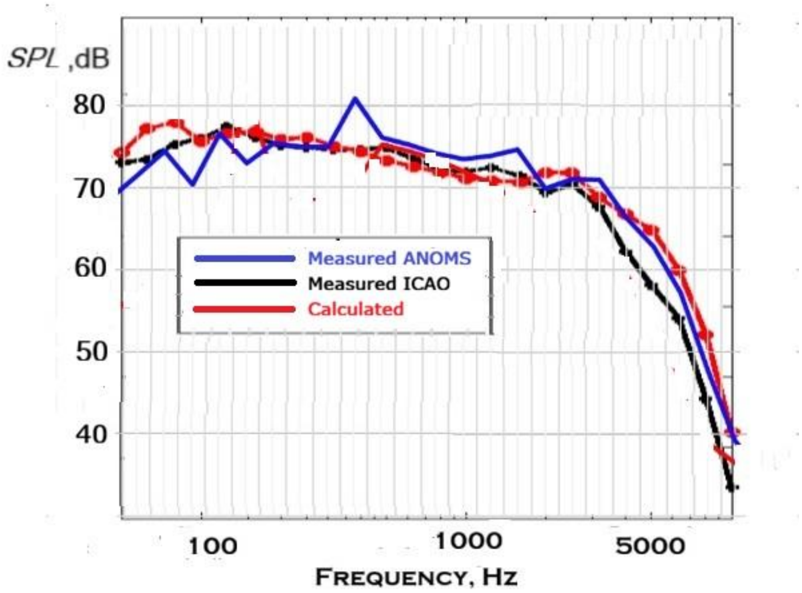


Fig. 9. Comparison between the measured SPL spectra for the Airbus-320neo departures (a) and arrivals (b) at the Gdansk airport by AN monitoring and flight noise trials close to certification requirements (Malbéqui, 2018): calculated spectra for arrivals include the contribution from dominating in aircraft overall SPL spectrum noise sources – engine fan, wing slats and flaps (Source: Authors' own work)

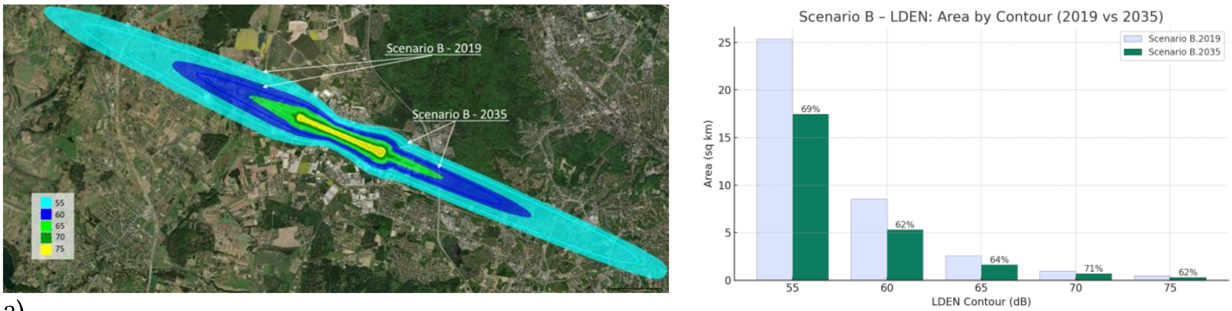
The Rolls-Royce UHBR turbofans are expected to be available in a few years for two most important aircraft classes – single-aisle narrowbody (for the short and middle rage distances) and two-aisles widebody (for the long-range distances) aircraft (Clean Aviation, 2024). The A321/320neo's (2015-year technology) noise footprint at take-off has been reduced by 50% compared to its predecessor the A321/320ceo (2000-year technology). To reach similar effect in future perspective aircraft with UHBR engines needs for the inclusion of the new NRT airframe designs also because their contribution in overall SPL spectrum at aircraft arrival noise is quite big. It is done at current step of EFACA project for the grounding of the overall noise performances of the LH_2-fuelled aircraft as following: the NPD data of the EFACA LH_2-fuelled aircraft for the departure flight modes are found equal to NPD data of the A320-270N reference aircraft minus 3 EPNdB; and for the arrival NPD data – the NPD data of the A320-270N reference aircraft minus 2 EPNdB (Table 2 data for UCON and HYDRO profiles). They were used for comparison of the regional airport (called EFACAport now) noise exposure for L_{DEN} (Fig. 10(a)) and L_{night} (Fig. 10(b)) in 2019 and 2035 air traffic scenarios as shown in Fig. 10. If the new Rolls-Royce UHBR turbofans will be available, the ACARE mid-term goal for noise will be achieved. All air traffic scenarios for EFACA port are developed according to the current state and forecast data at European regional airports to show the expected changes in AN exposure and to assess the adequacy of NRT applied in new aircraft designs.

5. Conclusions

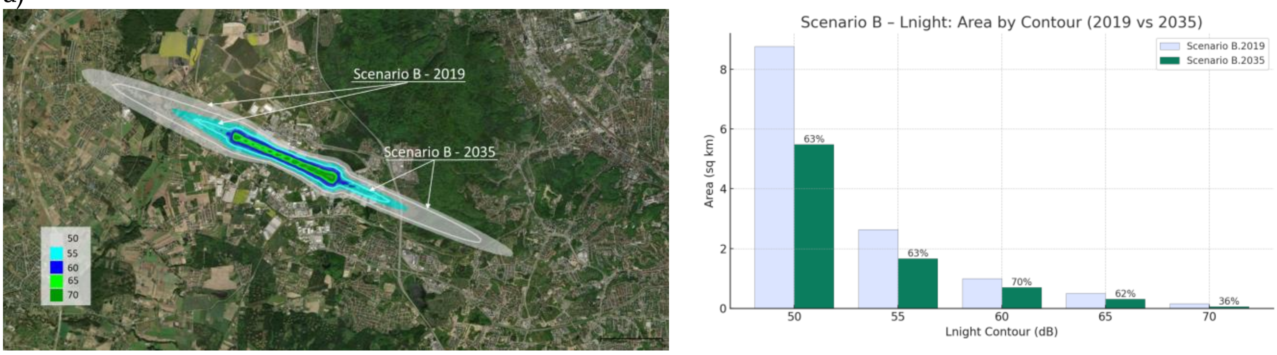
ACARE noise goals (ACARE, 2022) for new aircraft designs are defined for short-term (2030), mid-term (2035), and long-term (2050) perspectives in comparison with aircraft 2000-year reference noise performances and pre-COVID 2019-year traffic and fleet noise scenarios. Reference EFACA aircraft designs and traffic/fleet scenarios are consistent with these ACARE comparison requirements. The ICAO CAEP/13 meeting established a new Chapter 16 noise standard for new subsonic aircraft (ICAO, 2025), making it 6 dB quieter for large aircraft and 2 dB for small aircraft (cumulative EPNL reduction to Chapter 14 is considered), with applicability starting January 1, 2029, for new aircraft type designs. CAEP/13 also recommended a new Chapter 15 noise standard for supersonic aircraft, with a similar applicability date. These standards are part of an integrated ICAO effort to make noise and

CO_2 emissions standards more stringent simultaneously to drive the development of more sustainable aircraft designs – the EFACA aircraft concept also.

The specified operational and noise performances of the aircraft are modelled by means of the forecasting tool – called currently VALDES (**V**ehicle-**A**irport-f**L**eet-**DES**ign) platform or space for calculating the whole flight profile of the aircraft in accordance with the TLAR for reference and baseline aircraft designs (Makarenko et al., 2024). All the modules of the calculation platform were improved further during current stage of the EFACA project research to consider the low-noise and certification flight performances of the baseline aircraft in addition to normal operational conditions. The accuracy and adequacy of the approach were proved by comparison with available engine operational and aircraft flight performances with conventional power plants – for example for the reference aircraft Airbus-320neo.



a)



b)

Fig. 10. Comparison of the EFACAport noise exposure for L_{DEN} (a) and L_{night} (b) in 2019 and 2035 air traffic scenarios (Source: Authors' own work)

The EFACAport is introduced as a virtual EU regional airport in EFACA project and grounded in current aircraft noise exposure studies. Over the 80% of the flights per day are produced by narrowbodies (Airbus-320 and Boeing-737 of various modifications) within the distances covered by TLAR for the EFACA LH_2-fuelled aircraft and with still small and decreasing contribution of the SMR turboprops. The introduction of more advanced ANP (minus 2-3 dB for the NPD data for the departure flight modes) for the LH_2-fuelled aircraft configurations demonstrates a clear reduction in noise contour areas in middle perspective scenario compared to the baseline in 2019 (Fig. 10) and the ACARE mid-term goal for noise will be achieved. In such way the efficiency of the new aircraft designs is proved by noise certification limits and by airport noise scenario, which are required by current ACARE document (ACARE, 2022).

Abbreviations

ACARE	:	Advisory Council for Aviation Research and Innovation in Europe
ANZ	:	Aircraft Noise Zones
CAEP	:	Committee on Aviation and Environmental Protection
EFACA	:	Environmentally Friendly Aviation for all Classes of Aircraft
ICAO	:	International Civil Aviation Organization
IPCC	:	International Panel on Climate Change

LAQ : Local Air Quality

LH_2 : Liquid Hydrogen

LTAG : Long-Term Aspirational Goal

LTO : Long-Term Aspirational Goal

NRT : Noise Reduction Technology

TLAR : Top-Level Aviation Requirements

VALDES : Vehicle-Airport-fLeet-DESign

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