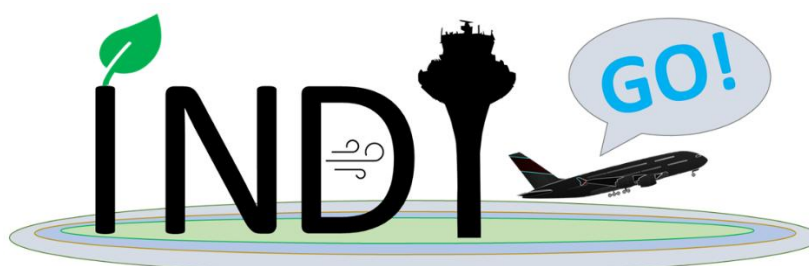


RESEARCH PROJECT MANAGEMENT

Document n°	INDIGO-D6.2
Refined greener LTO cycles. Environmental impact (LAQN) and human health impact	
Issue date	A03 - 30/09/2026

REVISION HISTORY TABLE		
VERSION N°	ISSUE DATE	REASON FOR CHANGE
A01	07/04/2026	First draft
A02	28/09/2026	Final draft for review
A03	30/09/2026	Final version of the document

Date of Issue: 30/09/2026



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.



Project: 101096055

INtegration and Digital demonstration of low-emission alrcraft technoloGies and airport Operations

INDIGO

Work package: WP6 - LAQN improvement from DHEP-LARW technology
development

Deliverable: D6.2 Refined greener LTO cycles. Environmental impact
(LAQN) and human health impact incl. margins from TRL



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

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List of Acronyms

Acronym	Definition
AERMOD	American Meteorological Society/EPA Regulatory Model
ASGS	Algebraic Sub-Grid Scale
BC	Black Carbon
BCN	Barcelona Airport
BenMAP-CE	Environmental Benefits Mapping and Analysis Program – Community Edition
BPF	Blade Passing Frequency
CAA	Computational Aeroacoustics
CFM56	CFM International CFM56 engine family
CO	Carbon Monoxide
COI	Cost of Illness
CRF	Concentration–Response Function
DHEP-LARW	Distributed Hybrid-Electric Propulsion – Large Aspect-Ratio Wing
DOE	Design of Experiments
DPR	Difference Percentage Ratio
DTM	Dortmund Airport
EEA/EMEP	European Environment Agency / European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
FEM	Finite Element Method
GDP	Gross Domestic Product
GIS	Geographic Information System
HA	Highly Annoyed
HC	Hydrocarbon
HSD	Highly Sleep-Disturbed
IMMIS+	IMMIS+ noise assessment / fly-over tool
LAE	Sound Exposure Level
LAQ	Local Air Quality
LAQN	Local Air Quality and Noise
LES	Large Eddy Simulations
LTO	Landing and Take-Off
LDEN	Day-Evening-Night Sound Level
Lnight	Night-time Sound Level
MAD	Madrid Airport
MHC	Methane Hydrocarbons
NOx	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
OECD-ENV	OECD Environment Directorate
PC	Pollutant Concentrations
PD	Pollutant Dispersion
PLT	Pollutant/trajectory output file format used by RAMS
PM	Particulate Matter



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POD	Proper Orthogonal Decomposition
PPP	Purchasing Power Parity
RANS	Reynolds-Averaged Navier–Stokes
RAMS	Regional Atmospheric Modeling System
REF	Reference scenario
RIX	Riga International Airport
RMSE	Root Mean Square Error
RPM	Revolutions Per Minute
SOC	State of Charge
SOL	Solution scenario
SPL	Sound Pressure Level
SPoL	Sound Power Level
STATFOR	EUROCONTROL Statistics and Forecast Service
TRL	Technology Readiness Level
UHC	Unburned Hydrocarbons
VOC	Volatile Organic Compounds
VSL	Value of a Statistical Life
WHO	World Health Organization
WTP	Willingness To Pay



1. Introduction, objectives and assumptions

The INDIGO project addresses the environmental and operational challenges associated with aviation in the vicinity of airports, with a particular focus on local air quality, noise, and low-altitude operations. The project explores innovative aircraft and operational solutions aimed at reducing emissions and acoustic impacts during the most sensitive phases of flight, including taxi, take-off, and landing. In this context, INDIGO considers a mid-range aircraft concept integrating distributed hybrid electric propulsion, large aspect-ratio wings, and novel near-airport operational strategies, with the broader ambition of supporting the transition towards net-zero aviation.

The project also recognizes that the assessment of such technologies is affected by uncertainty, particularly in relation to the performance of low-TRL solutions and their integration into future airport and aircraft operations. For this reason, INDIGO combines modelling, simulation, and validation activities to examine the potential of these concepts under realistic operational conditions, and to improve the methods used to estimate their environmental impact near airports.

The specific objectives of this deliverable are:

1. To define and apply a consistent **simulation framework** for the assessment of the INDIGO solution scenarios, focusing on the operational phases and trajectories most relevant to emissions and local environmental impacts in the airport area.
2. To **compare baseline and solution scenarios** under harmonized traffic and modelling assumptions, ensuring that the differences observed across cases can be attributed to the INDIGO-related changes rather than to inconsistencies in the simulation setup.
3. To **quantify the impact of the proposed solutions** on local air quality, noise exposure, and related health and economic indicators, using the modelling chain defined for the evaluation activity.
4. To **integrate high-fidelity and low-fidelity modelling** approaches where appropriate, so as to combine detailed trajectory-based analysis with full-LTO coverage when required by the scope of the assessment.
5. To apply **correction, normalization, and data-fusion procedures** that improve the consistency of the outputs and allow the results to be compared across airports and scenarios.
6. To **assess the sensitivity of the results** to the main technological and operational parameters considered in the study, especially battery density and payload variables.
7. To provide a robust evidence base for **evaluating the environmental performance** of the INDIGO concept and supporting subsequent project-level decision-making.



The following hypotheses underpin the methodology and scope of this document:

1. Flight simulation scope

The flight trajectory simulation is restricted to operations below 3000 ft, including taxiing up to the gate, as these phases are considered the most relevant for the assessment of local environmental impacts around the airport.

2. Traffic representation and sequencing

For the RAMS-based simulations, traffic sequencing is assumed to be representative of the selected airport cases. Specifically, automatic sequencing is applied for DTM and BCN, while trace-based sequencing is used for RIX and MAD. In addition, the use of one-week traffic windows for DTM and RIX, and one-day traffic windows for BCN and MAD, is assumed to provide a balanced representation of traffic conditions across the different case studies.

3. Progressive substitution of the INDIGO aircraft model

The INDIGO aircraft model developed in previous work packages is progressively introduced into the solution scenarios. This substitution is carried out only when the aircraft remains flyable and replaceable according to the estimated fleet composition, ensuring that the scenario remains operationally feasible. Flyability and replaceability criteria do not allow INDIGO aircraft to be replaced in the same proportion for all city-pairs in all scenarios, but it depends on the type of traffic available. Therefore, improvements in terms of LAQ might be more remarkable between SOL10 and SOL20, or between SOL20 and SOL30 scenarios, and with less drastic differences from SOL30 to SOL40 results, as from SOL30 to SOL40 there are not many available options left for INDIGO replacement.

4. Input data preprocessing

Due to limitations of the RAMS simulator, the traffic input data require correction and cleaning before simulation. It is assumed that this preprocessing does not invalidate the comparative analysis between scenarios, even if it results in small variations in the final INDIGO percentages and in the number of simulated flights.

5. Transferability of the RIX-based INDIGO model

The INDIGO aircraft performance model calibrated for RIX is assumed to be applicable to the remaining airports analyzed, under the working hypothesis that performance differences across the case studies are sufficiently limited for the purposes of this assessment.

6. Emissions modelling for LAQN analysis

Emission rates are calculated mainly for the airborne trajectory, while taxi-related emissions are represented through a more general approximation.



7. Data fusion methodology

Specific RIX slots are selected to calculate the correction factor used in the data fusion process. It is assumed that this correction factor can be extended to the rest of the traffic and to the other airports included in the study.

8. High-fidelity model limitations

Because of the limitations of the high-fidelity model, only airborne trajectory data from RIX are used, excluding taxi operations. Likewise, Black Carbon (BC) is not used for delta estimation in the high-fidelity framework and is therefore reported without an additional delta term.

9. Low-fidelity simulation coverage

The low-fidelity model is assumed to provide full LTO coverage, allowing the analysis to represent the complete landing and take-off cycle when high-fidelity data are not available or not applicable. As there is no delta for BC, the LAQ assessment will provide BC results with no delta value added.

10. Health and economic impact assessment

Before applying the correction factor, AERMOD outputs are post-processed in order to preserve the variability of the data, given the large differences in magnitude between values. For the impact assessment, the city of each country is assumed to be the relevant study area, including its districts and neighborhoods, so that the effects on urban populations can be captured regardless of the exact distance between the city and the airport.

11. Scope limitations

The health and economic analysis are not conducted for CO (Carbon Monoxide), BC and HC (Hydrocarbon). However, PM (Particulate Matter) and NO_x (Nitrogen Oxides) are the most critical pollutants contributing to health and economic impact, as stated in the literature analysed. For economic assessment, the noise impact with respect to VSL is not considered as the noise affection on this aspect (based on different studies included in WHO guidelines) is very limited and not sufficiently demonstrated, as the available COHORT studies on strokes and hypertension derived from noise exposure are of very low confidence.

12. Use of NO₂-based concentration–response functions for NO_x assessment

The epidemiological studies selected for the assessment of nitrogen-related health effects report concentration–response relationships for nitrogen dioxide (NO₂), whereas the air-quality modelling performed within INDIGO provides concentrations for total nitrogen oxides (NO_x, comprising NO and NO₂). Due to the absence of modelled NO₂ concentrations as a separate pollutant, the NO₂-based concentration–response functions are applied to the modelled changes in NO_x concentrations.

For the purposes of the health impact assessment, changes in modelled NO_x concentrations are therefore used as a proxy for changes in NO₂ exposure. This represents a methodological assumption and should be considered when interpreting the resulting health-impact estimates, since NO_x and NO₂ are not chemically or quantitatively equivalent.



13. Sensitivity analysis

The sensitivity analysis is based on three cases — low, medium, and high — defined by battery density and payload for a representative high-frequency RIX trajectory. These cases are assumed to capture the main variation in aircraft performance under the selected operating conditions.



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

2. Dataset

2.1. Riga airport

2.1.1. RIX traffic forecast

The definition of the future scenarios for RIX airport consisted of the following steps:

- Traffic demand forecast, obtaining the traffic expected in 2035, considering as well the airline expected growth to define the fleet compositions in that year. In this case, RIGA Airport provided their forecast information for the expected traffic increment between 2030 and 2040. This information was presented as traffic increment per distance groups (the city-pairs were later classified into these groups, before the traffic growth assignment). Next table shows the expected traffic increment for commercial flights:

Distance (km)	Flights in 2030	Flights in 2040	Increment 2030-2040
0-499	20238	25959	28.27%
500-999	15436	19798	28.26%
1000-1499	14619	18752	28.27%
1500-1999	15066	19325	28.27%
2000-2499	5216	6690	28.26%
2500-2999	1872	2400	28.21%
3000-3499	1770	2271	28.31%
3500-3999	920	1180	28.26%
4000-4499	1103	1415	28.29%
4500-4999	414	531	28.26%

Table 1: Riga Airport Traffic forecast 2030-2040 (Commercial flights)

- Reference Scenario definition, considering the traffic and fleet forecast, and adding the optimal trajectories obtained in T4.3. For the expected traffic in 2035, the most frequent procedures were assigned, selecting only compatible aircraft (in case there is no procedure compatible with the aircraft available in the fleet composition, the most similar aircraft would be assigned instead).
- Solution Scenarios definition, based on the reference Scenario, and replacing part of the aircraft by INDIGO. This replacement was applied for both baseline and added traffic (from 2025 to 2035), and considering the most optimal procedures compatible with INDIGO aircraft.

Reference and Solution Scenarios definition process will be the same for all the UCs, so it will not be explained again in the following sections.



2.1.2. RIX Scenarios definition

The final process was the definition of the future scenarios. This process was common for all the Use Cases, and the main purpose was to define different realistic scenarios where the INDIGO aircraft is included in the fleet of the airlines of 2035, and to assess the benefit of this inclusion in WP6.

For each Solution Scenario, part of the flights would be covered by INDIGO instead of the conventional aircraft. These changes were applied not only to new flights (the added traffic from 2025 to 2035) but also to the baseline ones. The purpose of this is to perform a realistic forecast, as it is expected that the INDIGO aircraft would not only be used to cover the increasing traffic, but also part of the baseline. Indeed, the criteria to replace the flights by INDIGO aircraft in different scenarios was defined trying to keep realism:

- ✓ INDIGO aircraft would be assigned only to procedures flyable by this new aircraft.
- ✓ The new aircraft would be assigned trying to balance the replacement in all city-pair ranges:
 - 150 to 500NM: 30% of the replaced flights
 - 500 to 1000NM: 30%
 - 1000 to 1400NM: 30%
 - 1400 to 1500NM: 10%

Considering this criterion, the different scenarios were defined:

- Reference Scenario (REF): The expected traffic situation in 2035 according to the forecast, only considering the conventional aircraft in the predicted fleet compositions. Best-in-class combinations from the conventional cost function were used to define the traffic.
- Solution 10I-90C (SOL10): For the traffic expected in the reference scenario, 10% of flights will be operated with INDIGO aircraft, and 90% with the conventional ones.
- Solution 20I-80C (SOL20): For the traffic expected in the reference scenario, 20% of flights will be operated with INDIGO aircraft, and 80% with the conventional ones.
- Solution 30I-70C (SOL30): For the traffic expected in the reference scenario, 30% of flights will be operated with INDIGO aircraft, and 70% with the conventional ones.
- Solution Optimal (SOL40): For the traffic expected in the reference scenario, 40% of flights will be operated with INDIGO aircraft, and 60% with the conventional ones. This is considered as optimal scenario considering that 100% INDIGO would not be realistic even in future scenarios.

2.1.3. RIX final dataset of RAMS

For the simulation carried out within T6.3, RIX traffic dataset was used to select the most adequate time period to perform this task. The week from the 21st to the 27th of August of 2023 was identified as the representative week for RIX traffic, so this period was finally chosen for this purpose.



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In the solution scenario, a selected number of conventional aircraft are replaced with INDIGO aircraft in order to assess their environmental impact. To study with which percentage of INDIGO flights can bring a significant benefit, there are 4 sub-solution scenarios with 10%, 20%, 30% and 40% of replaceability, following the criteria explained in the previous section.

Scenario	Total flight number	Total Landing	Total Take-Off	Number of INDIGO (%)
REF	1021	492	529	0
SOL10	1021	492	529	115 (11.26%)
SOL20	1021	492	529	221 (21.65%)
SOL30	1021	492	529	328 (32.13%)
SOL40	1021	492	529	435 (442.61%)

Table 2: RIX final dataset

2.2. Dortmund airport

2.2.1. DTM traffic forecast

The definition of the future scenarios for RIX airport consisted of the traffic demand forecast, obtaining the traffic expected in 2035, considering as well the airline expected growth to define the fleet compositions in that year. In this case, EUROCONTROL STATFOR Forecast Model was applied [25], in order to obtain the traffic expected in Dortmund Airport in 2035. In addition, Dortmund Airport personnel provided their forecast for 2030, assuming 3% of annual increase. This was taken into consideration and corrected with STATFOR forecast, so as to obtain the final increase rates that would be used for the future scenario definition.

2.2.2. DTM Scenarios definition

In a similar procedure as with RIX Use Case, solution scenarios were prepared with a selected number of conventional aircraft replaced by INDIGO aircraft in order to assess their environmental impact. 4 sub-solution scenarios with 10%, 20%, 30% and 40% of replaceability were defined, following the criteria explained in the previous section.

The criteria to replace the flights by INDIGO aircraft in different scenarios was defined trying to keep realism:

- ✓ INDIGO aircraft would be assigned only to procedures flyable by this new aircraft.
- ✓ The new aircraft would be assigned trying to balance the replacement in all city-pair ranges:
 - 150 to 500NM: 30% of the replaced flights
 - 500 to 1000NM: 30%
 - 1000 to 1400NM: 30%
 - 1400 to 1500NM: 10%



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2.2.3. DTM final dataset of RAMS

For the simulation carried out within T6.3, DTM traffic dataset was used to select the most adequate time period to perform this task. The week from the 3rd to the 9th of July of 2023 was identified as the representative week for DTM traffic, so this period was finally chosen for this purpose. This dataset was used to define reference and solution scenarios to be simulated in RAMS:

Scenario	Total flight number	Total Landing	Total Take-Off	Number of INDIGO (%)
REF	447	236	211	0
SOL10	447	236	211	43 (9.62%)
SOL20	447	236	211	88 (19.69%)
SOL30	447	236	211	131 (29.31%)
SOL40	447	236	211	177 (39.60%)

Table 3: DTM final dataset

2.3. Madrid airport

2.3.1. MAD traffic forecast

The definition of the future scenarios for MAD airport consisted of the following steps:

- Traffic demand forecast, obtaining the traffic expected in 2035, considering as well the airline expected growth to define the fleet compositions in that year. In this case, EUROCONTROL STATFOR Forecast Model was applied, in order to obtain the traffic expected in Madrid Airport in 2035.
- DELFOS, which is an in-house Forecast Model developed by CRIDA, was also used to correct the traffic increment rates obtained with STATFOR Model. A calibration was performed, comparing these two models with historic data, to choose the most accurate prediction for each city-pair expected traffic rate for 2035.

2.3.2. MAD Scenarios definition

In a similar procedure as with RIX and DTM Use Cases, solution scenarios were prepared with a selected number of conventional aircraft replaced by INDIGO aircraft in order to assess their environmental impact. 4 sub-solution scenarios with 10%, 20%, 30% and 40% of replaceability were defined, following the criteria explained in the previous section.

The criteria to replace the flights by INDIGO aircraft in different scenarios was defined trying to keep realism:



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

- ✓ INDIGO aircraft would be assigned only to procedures flyable by this new aircraft.
- ✓ The new aircraft would be assigned trying to balance the replacement in all city-pair ranges:
 - 500NM to 1000NM: 50% of the replaced flights
 - 1000NM to 1500NM: 50%

2.3.3. MAD final dataset of RAMS

For the simulation carried out within T6.3, MAD traffic dataset was used to select the most adequate time period to perform this task. The week from the 10th to the 16th of July of 2023 was identified as the representative week for MAD traffic.

However, the large amount of traffic made the dataset very difficult to be simulated, so finally the 12th of July was chosen for this purpose, which is the second busiest day of the representative week. This dataset was used to define reference and solution scenarios to be simulated in RAMS:

Scenario	Total flight number	Total Landing	Total Take-Off	Number of INDIGO (%)
REF	1112	560	552	0
SOL10	1112	560	552	110 (9.89%)
SOL20	1112	560	552	171 (15.38%)
SOL30	1112	560	552	340 (30.58%)
SOL40	1112	560	552	452 (40.65%)

Table 4: MAD final dataset

2.4. Barcelona airport

2.4.1. BCN traffic forecast

The definition of the future scenarios for BCN airport consisted of the following steps:

- Traffic demand forecast, obtaining the traffic expected in 2035, considering as well the airline expected growth to define the fleet compositions in that year. In this case, EUROCONTROL STATFOR Forecast Model was applied, in order to obtain the traffic expected in Barcelona Airport in 2035.
- DELFOS, which is an in-house Forecast Model developed by CRIDA, was also used to correct the traffic increment rates obtained with STATFOR Model. A calibration was performed, comparing these two models with historic data, to choose the most accurate prediction for each city-pair expected traffic rate for 2035.



2.4.2. BCN Scenarios definition

In a similar procedure as with RIX, DTM and MAD Use Cases, solution scenarios were prepared with a selected number of conventional aircraft replaced by INDIGO aircraft in order to assess their environmental impact. 4 sub-solution scenarios with 10%, 20%, 30% and 40% of replaceability were defined, following the criteria explained in the previous section.

The criteria to replace the flights by INDIGO aircraft in different scenarios was defined trying to keep realism:

- ✓ INDIGO aircraft would be assigned only to procedures flyable by this new aircraft.
- ✓ The new aircraft would be assigned trying to balance the replacement in all city-pair ranges:
 - 500NM to 1000NM: 50% of the replaced flights
 - 1000NM to 1500NM: 50%

2.4.3. BCN final dataset of RAMS

For the simulation carried out within T6.3, BCN traffic dataset was used to select the most adequate time period to perform this task. The week from the 10th to the 16th of July of 2023 was identified as the representative week for BCN traffic.

However, the large amount of traffic made the dataset very difficult to be simulated, so finally the 10th of July was chosen for this purpose, which is the second busiest day of the representative week. This dataset was used to define reference and solution scenarios to be simulated in RAMS:

Scenario	Total flight number	Total Landing	Total Take-Off	Number of INDIGO (%)
REF	1108	522	586	0
SOL10	1108	522	586	109 (9.84%)
SOL20	1108	522	586	219 (19.77%)
SOL30	1108	522	586	329 (29.69%)
SOL40	1108	522	586	443 (39.98%)

Table 5: BCN final dataset



3. Methodology

3.1. Fast-Time Simulation using RAMS

RAMS Plus is a fast-time simulation platform widely used in aviation research and operational studies to model aircraft trajectories, airport operations, air traffic management procedures, and associated environmental impacts. The simulator reproduces aircraft movements in a realistic operational environment, including all phases of the flight profile such as taxi-out, take-off, climb, approach, landing, and taxi-in. It enables detailed analysis of traffic flows, aircraft performance, fuel consumption etc. under different operational scenarios.

In the study, RAMS Plus was selected because it enables the rapid generation of realistic tracks and operational scenarios for aircraft movements during the LTO cycle. The simulator can efficiently reproduce aircraft trajectories for take-off, landing, approach, departure, and taxiing operations under representative traffic conditions, making it well suited for large-scale environmental assessments.

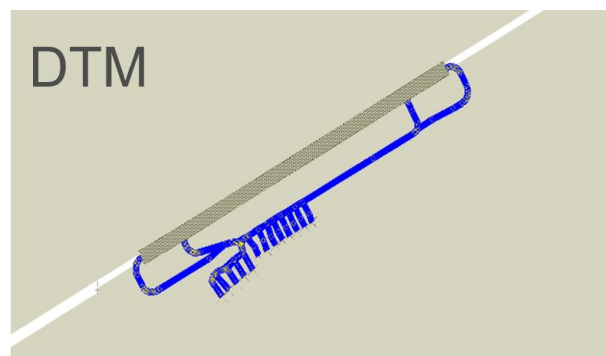


Figure 1: DTM airport in RAMS



Figure 2: RIX airport in RAMS



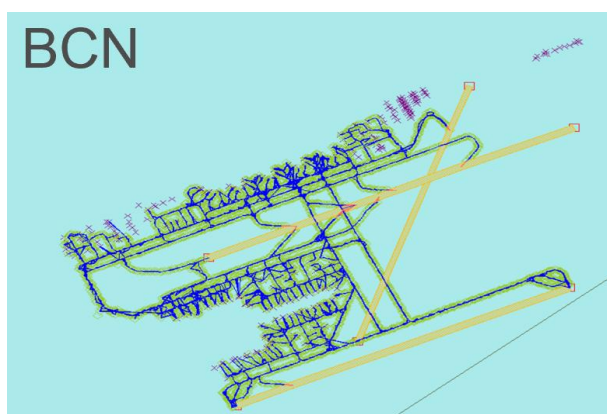


Figure 3: BCN airport in RAMS



Figure 4: MAD airport in RAMS

3.2. High-fidelity simulations (LES)

Large Eddy Simulations (LES) were carried out to accurately predict the transport of pollutants in the airport vicinity. Such simulations considered the pollutants issued during the flight and their interaction with the wind up to a height of 900 m. Due to the high computational cost and the number of simulations some simplifications had to be introduced to keep simulations affordable. To this purpose a methodology to capture the interaction of the pollutants emitted during the flight and the surrounding was developed which is intended to be general. However, it is important to mention that such simulations are not targeted to reproduce the real airport operation during long times due to the prohibitive computational cost in which they would incur. On the contrary, flights were run isolated. In the project simulations only comprised the air traffic in the Riga airport. Simulations were carried out for both conventional aircrafts as well as the optimized (solution) aircraft configuration generated during the project. A detailed description of the hypotheses and construction of initial and boundary conditions for the high-fidelity simulations can be found in deliverable D6.1 of this project. Therefore, here only a brief description will be provided for the sake of completeness.



3.2.1. Hypotheses

The hypotheses stated in the following are targeted to reduce the computational cost without compromising the accuracy of the results. The interested reader is referred to deliverable D6.1 [1] for the justifications of the hypotheses.

- Only one single trajectory is computed per simulation.
- Taxi phases are not considered due to the relative low emission during such phases in comparison with the others.
- Pollutants cloud issued during the flight is imposed as an initial condition since the flight trajectory lasts for approximately for 1 minute and 30 seconds (below 900 m) and the wind velocities are relatively low.
- Such initial conditions are generated from a precursor simulation in a much smaller domain and refined mesh to account for the interaction of the wing tip vortices and the pollutants.
- The original domain (16 x 8 x 0.9 km³), the domain was divided into two subdomains (of dimensions 8 x 8 x 0.9 km³), north and south, including each one the north and the south runways of the airport, respectively.
- The wind velocity direction and modulus (at 10 m height) were extracted from airport measurements. However, the spatially averaged wind velocity was kept constant in modulus and direction in time.
- Terrain was assumed flat and no buildings were considered due to the low height of the buildings of the airport and the surroundings.
- Simulations were carried out assuming constant flow properties (density and viscosity) and no atmosphere thermal stratification was considered.
- Aircraft plumes are assumed to be chemically inert. Also the flow is solved under isothermal assumption.

3.2.2. Governing equations and numerical set-up

The transport equations to be solved correspond to continuity, Navier-Stokes and pollutants for constant density flow. Due to the high Reynolds numbers developed in these simulations (turbulent boundary layers), these equations were solved in the frame of Large Eddy Simulations (LES) where the large and medium-size temporal-spatial scales are solved while the small-size structures are modelled. Boussinesq and gradient diffusion hypotheses are assumed to model the turbulent transport.

The pollutants transported in the simulations are carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons (UHC) and particulate matter (PM). All of them share the same molecular diffusion coefficient except PM for which a null molecular diffusion coefficient value is used since it consists of solid particles. Fields are, however, very insensitive to the molecular diffusion coefficient due to the dominance of the turbulent diffusion coefficient.



Regarding the numerical set-up, simulations were carried out with Alya, the multi-physics code developed at the CASE Department from the Barcelona Supercomputing Center (BSC) [26]. Alya is based on the Finite Element Method (FEM) in which transport equations are solved in their weak form. Second order spatial discretization is used while an explicit Runge-Kutta 3rd order scheme is applied. The ASGS (Algebraic Sub-Grid Scale) model is used for the stabilization of the pollutants transport equations [27][28]. An adaptive time step based on the Courant-Friedrich-Lewis condition and the critical time step imposed by diffusion is computed at each instant.

The mesh of $8 \times 8 \times 0.9 \text{ km}^3$ used in the current calculations is structured composed of hexahedra. To improve discretization the domain is divided in vertical direction in two regions: the first one extends up to 60 m, with a uniform vertical cell side length of 3 m, while the second one extends over the rest of the domain, that is, from 60 to 900 m with an expansion ratio of 1.007. The direction parallel to the projection of the trajectories (x) is uniform with a cell length side of 6 m while the y direction has an expansion ratio of 1.0039 with a minimum cell length side of 6 m. The mesh is composed of 100.9 M nodes (degrees of freedom) and 99.97 M cells. A second mesh of $5 \times 12 \times 0.9 \text{ km}^3$ was also used and was defined in a similar manner. Mesh nodes and cells are also 100.9 M and 99.97 M, respectively.

A brief description of the initial and boundary conditions is given in the following.

3.2.3. Initial conditions

For the initial conditions the domain is split in two parts, a first region perturbed by the aircraft, which comprises volume around the trajectory, and a second one of the flow not perturbed by the aircraft:

- For the first region precursor simulations are carried out in a tri-periodic refined cuboid domain where the effect of the aircraft on the air is created by simulating the reaction of lift and drag on the air by imposing a thin sheet of forces according to Lin et al., 2017. In such simulations the interaction of the induced air motion with exhaust gases plumes is also modelled. The fields from these simulations are stored in databases parametrized as a function of the circulation (assumed to be directly related to the aircraft velocity) and time. Such fields (velocity and pollutants) are imposed in the airport simulation after interpolation, based on the local velocity of the aircraft in each of the segments composing the trajectory.



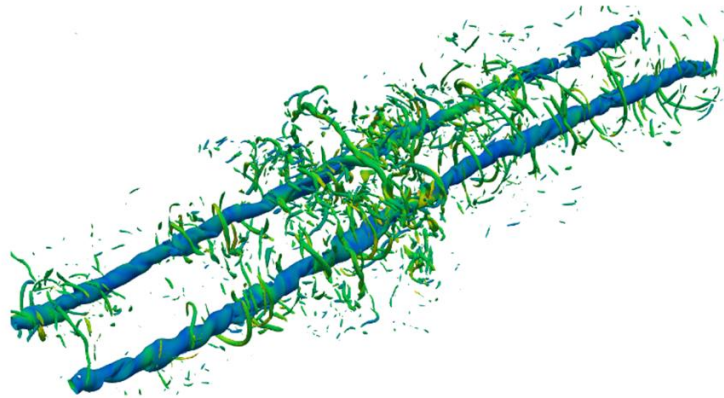


Figure 5: 3D view of the wing-tip vortices

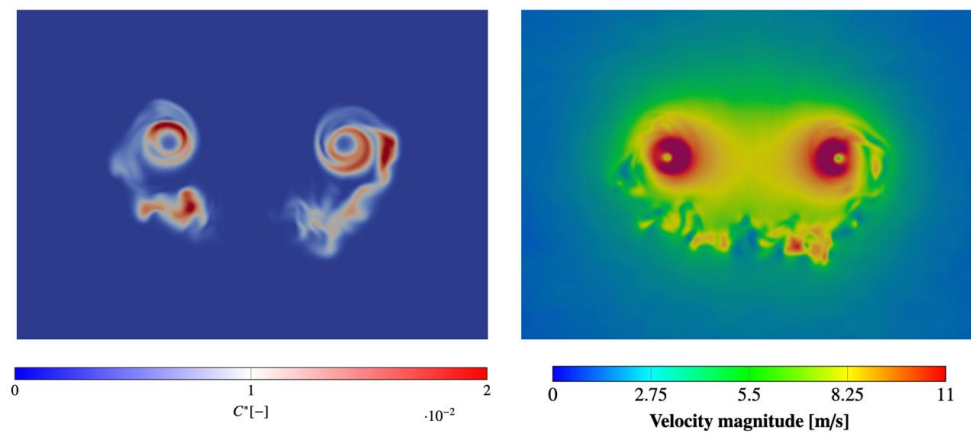


Figure 6: Slice of the wing-tip vortices created by the interaction of the aircraft with the air. The plane is normal to the aircraft trajectory. Left: scalar field representing the pollutants; right: velocity magnitude field.

- The second region consists of the zone unperturbed by the aircraft during its flight. In this region the interaction of the flow with the ground produces a turbulent boundary layer. To reduce the computational effort of simulating the turbulent boundary layer for each case a precursor simulation was carried out for a representative wind velocity. For the final simulations this velocity field produced by the precursor simulation was mapped after being scaled, according to the mean wind velocity modulus of the final simulation and rotated to impose the corresponding wind direction.

3.2.4. Boundary conditions

Regarding the boundary conditions these were:

- For the ground a wall law was imposed with a roughness length of 0.03 m according to the methodology described in Owen et al., 2020.



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

- A Dirichlet boundary condition was imposed based on the average velocity profile from Monin-Obukhov (M-O) theory for the case of no thermal stratification, which follows a logarithmic profile. The profile is determined from the knowledge of the velocity at 10 m height, data which was taken from experimental measurements at the airport, while the roughness length which was taken as 0.03 m, representative of a flat terrain with grass and isolated obstacles.
- For the lateral walls of the parallelepiped through which the wind exits from the domain, an outlet condition was imposed (null gradient).
- For the lateral walls of the parallelepiped through which the wind enters the domain, an inlet condition was imposed. This condition was generated based on the precursor simulation of the turbulent boundary layer described in the initial conditions section following similar ideas to those applied to inlet conditions for pipes at high Reynolds numbers [1].

An illustrative comparison between both models is shown in the following for a landing and a take-off of the solution aircraft. An example of the solutions obtained with the method is represented in next figure which shows the pollutants maps at a height of 1.5 m.

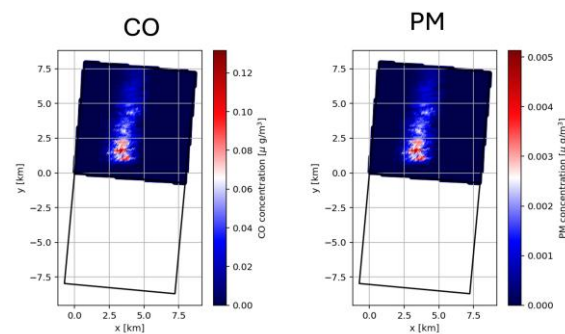


Figure 7: Pollutants maps at a height of 1.5 m. Solutions for the landing of the solution aircraft after 2400 s after the end of the trajectory. Representation for the north domain. Wind velocity of 1.54 m/s (10 m height) and wind direction of 270°.

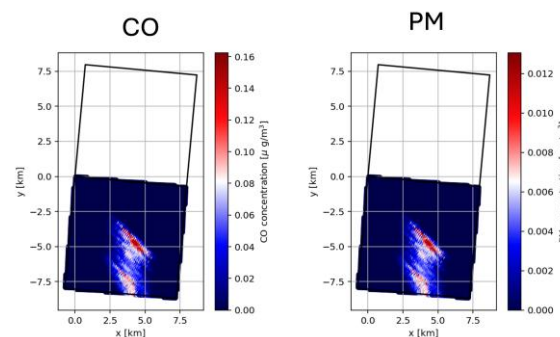


Figure 8: Pollutants maps at a height of 1.5 m. Solutions for the take-off of the conventional aircraft after 2400 s after the end of the trajectory. Representation for the south domain. Wind velocity of 2.57 m/s (10 m height) and wind direction of 320°.



3.3. Low-fidelity simulations (AERMOD)

Gaussian models calculate the vertical displacement (buoyancy and momentum effects) of the plume at the outlet of an emission source, according to the gas exit velocity and temperature. They are based on the advection–diffusion equation and use simplifications to adapt the model to specific study cases.

The American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee introduced the modelling system AERMOD, that incorporated air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain.

There are two input data processors that are regulatory components of the AERMOD modelling system:

- ✓ AERMET: a meteorological data preprocessor.
- ✓ AERMAP: a terrain data preprocessor.

3.3.1. Outputs from the model

The basic types of printed output available with AERMOD are:

- Summaries of pollutant concentration values (highest, second highest, etc.) by receptor for each different combination of averaging period and source group.
- Summaries of overall maximum values (e.g. the maximum 50) for each averaging period and source group combination.
- Tables of concurrent values are summarized by receptor for each combination of averaging period and source group, for each day of data processed.

3.3.2. Pollutant concentrations calculation (PC)

Trajectory samples are obtained from the simulations conducted through RAMS Plus FTS. RAMS Plus generates a set of output files containing all the information from the traffic and the scenario. All the data generated in the RAMS output file “FlightEvent” is converted into an intermediary CSV file with all the tracks and their associated values that are required (such as ATOT, AOBT, aircraft model, speeds, altitude...).





- The gaseous emissions are obtained from the EEA/EMEP emission inventory guidebook [2] for the conventional aircraft, with the exception of A320 and B737 emissions that are directly provided from the engine model used in WP2 of this project.

○

Engine fuel burn and emissions data				
	Engine thrust setting (% of maximum thrust)			
	7%	30%	85%	100%
Rate of fuel burn (kg/s/engine)	0,1040	0,3120	0,9350	1,132
Rate of emission of CO ¹ (kg/s/engine)	0,002433600	0,0007176000	0,0008415000	0,001018800
Rate of emission of HC ² (kg/s/engine)	0,0004784000	0,0001560000	0,0001870000	0,0002264000
Rate of emission of NOx ³ (kg/s/engine)	0,0004472000	0,003120000	0,02169200	0,03169600
Rate of emission of PM _{vol-org} ⁴ (kg/s/engine)	0,000002951730	0,000008775000	0,00001421200	0,00002603600
Rate of emission of PM _{vol-sul} ⁵ (kg/s/engine)	0,000005091840	0,00001527552	0,00004577760	0,00005542272
Rate of emission of PM _{non-vol} ⁶ (kg/s/engine)	0,0000005538810	0,0000009654900	0,00003150280	0,00004504740
Rate of emission of PM _{total} ⁷ (kg/s/engine)	0,000008597451	0,00002501601	0,00009149240	0,0001265061

Notes

1 CO is carbon monoxide.
2 HC is unburnt hydrocarbons.
3 NOx are mono-nitrogen oxides (NO and NO₂)
4 PM_{vol-org} is volatile organic particulate matter (PM). (Turbofan engines only)
5 PM_{vol-sul} is volatile sulphuric PM. (Turbofan engines only)
6 PM_{non-vol} is non-volatile PM. (Turbofan engines only)
7 PM_{total} is all types of PM added together. (Turbofan and piston engines only)

Figure 11. Example of emission factors at different engine thrust setting for the A320 with CFM56 engines [2]

- The particulate matter emissions are also estimated from EEA/EMEP in terms of kg/s/engine for conventional aircraft.
- INDIGO gaseous emissions are estimated by following the methodology described in D6.1, chapter 3 “Description of the emission rates calculation” [1].

segment	band_label_ft	HC_kgmin_mean	NOX_kgmin_mean	CO_kgmin_mean
climb	0-100	0.00210	0.51083	0.01953
climb	100-200	0.00210	0.50925	0.01954
climb	200-300	0.00210	0.50716	0.01955
climb	300-400	0.00210	0.50509	0.01956
climb	400-500	0.00210	0.50317	0.01957
climb	500-600	0.00210	0.50126	0.01958
climb	600-700	0.00210	0.49978	0.01960
climb	700-800	0.00210	0.49938	0.01960
climb	800-900	0.00210	0.49904	0.01961
climb	900-1000	0.00210	0.49875	0.01962
climb	1000-1100	0.00211	0.49856	0.01963
climb	1100-1200	0.00211	0.49838	0.01964
climb	1200-1300	0.00211	0.49801	0.01966
climb	1300-1400	0.00211	0.49747	0.01967
climb	1400-1500	0.00211	0.49692	0.01968
climb	1500-1600	0.00211	0.49612	0.01969



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

segment	band_label_ft	HC_kgmin_mean	NOX_kgmin_mean	CO_kgmin_mean
climb	1600-1700	0.00212	0.49516	0.01971
climb	1700-1800	0.00212	0.49399	0.01972
climb	1800-1900	0.00212	0.48786	0.01983
climb	1900-2000	0.00213	0.47960	0.01997
climb	2000-2100	0.00213	0.47109	0.02012
climb	2100-2200	0.00213	0.45967	0.02031
climb	2200-2300	0.00214	0.44744	0.02052
climb	2300-2400	0.00215	0.43527	0.02074
climb	2400-2500	0.00215	0.42339	0.02095
climb	2500-2600	0.00216	0.41157	0.02117
climb	2600-2700	0.00216	0.40095	0.02135
climb	2700-2800	0.00216	0.39508	0.02139
climb	2800-2900	0.00215	0.38971	0.02141
climb	2900-3000	0.00215	0.38434	0.02144

Table 6: Example of INDIGO emission factors for one mission simulated at different altitude level ranges

- Finally, INDIGO particulate emissions are obtained from the estimated fuel consumption, calculated by RAMS Plus by taking into consideration its performance parameters (horizontal and vertical speed, MTOW, length, wingspan, etc.) and building a BADA-like format model. Once fuel consumption rate is estimated for each segment of the trajectory, conversion to PM emissions is calculated (considering A320 aircraft as a reference, and obtaining rates from EEA/EMEP inventory, “proxy CFM56-5B4/P”) as:

$$PM \left(\frac{kg}{s} \right) = Fuel \left(\frac{kg}{s} \right) * \frac{\frac{kg PM}{s*engine} (A320)}{\frac{kg Fuel}{s*engine} (A320)}$$

- The **INP file** serves as a configuration file, containing extensive information about the simulation setup. It includes the name of the corresponding HRE file, a detailed description of the segments referenced in the HRE file (such as segment names, geographic coordinates, and altitudes), descriptions of the receptors (locations where pollutant concentrations are measured), the mapping of segments to each flight, and other metadata necessary for AERMOD to perform the calculations correctly.
- The **SFC** and **PFL** files contain all the meteorological information required to execute the model. This information is obtained from METAR records and grib files.

Once these files were prepared, they were introduced to the AERMOD tool to calculate pollutant concentrations. Each HRE and INP file required a separate execution of the



AERMOD tool, as the tool processes each set independently. The output of each execution was a set of files in PLT format, each of them containing pollutant concentration data at each receptor location for each flight described in the corresponding INP file.

```

* AERMOD ( 19191): INDIGO
* AERMET ( 15181):
* MODELING OPTIONS USED: NonDEFAULT CONC FLAT FLGPOL ALPHA RURAL MMIF_Data
* POST/PLOT FILE OF CONCURRENT 1-HR VALUES FOR SOURCE GROUP: F137
* FOR A TOTAL OF 43296 RECEPTORS.
* FORMAT: (3(1X,F13.5),3(1X,F8.2),2X,A6,2X,A8,2X,I8.8,2X,A8)

```

X	Y	AVERAGE CONC	ZELEV	ZHILL	ZFLAG	AVE	GRP	DATE	NET ID
688280.53994	6318435.69689	0.00119	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54101	6318335.69670	0.00120	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54207	6318235.69652	0.00120	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54313	6318135.69633	0.00120	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54419	6318035.69614	0.00120	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54526	6317935.69595	0.00121	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54632	6317835.69576	0.00121	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54738	6317735.69557	0.00121	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54844	6317635.69538	0.00122	0.00	0.00	3.00	1-HR	F137	23010913	
688280.54951	6317535.69519	0.00122	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55057	6317435.69500	0.00122	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55163	6317335.69481	0.00123	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55270	6317235.69463	0.00123	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55376	6317135.69444	0.00123	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55482	6317035.69425	0.00123	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55588	6316935.69406	0.00124	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55695	6316835.69387	0.00124	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55801	6316735.69368	0.00124	0.00	0.00	3.00	1-HR	F137	23010913	
688280.55907	6316635.69349	0.00124	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56014	6316535.69330	0.00125	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56120	6316435.69311	0.00125	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56226	6316335.69292	0.00125	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56333	6316235.69273	0.00125	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56439	6316135.69254	0.00126	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56545	6316035.69236	0.00126	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56652	6315935.69217	0.00126	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56758	6315835.69198	0.00126	0.00	0.00	3.00	1-HR	F137	23010913	
688280.56864	6315735.69179	0.00127	0.00	0.00	3.00	1-HR	F137	23010913	

Figure 12 - Example of a PLT output file

3.3.3. Pollutant dispersion (PD)

The model calculates hourly averages for each of the receptors at 1.5-meter height, belonging to the breathing zone, as stated in the Regulations identified in D1.1 (INDIGO Project, 2023) [3].

This process is done for the four UCs selected in the project (Madrid, Barcelona, Riga and Dortmund). Terrain data used is obtained from the available MDTs, developed in tasks T1.3 and T4.1 of this project, this data is introduced as ZELEV and ZHILL values.

Simulations are repeated for every scenario, and PLT files are generated. These files are subsequently modified by adding the delta values calculated in task T6.5 following the methodology described in section 3.4 of this document.



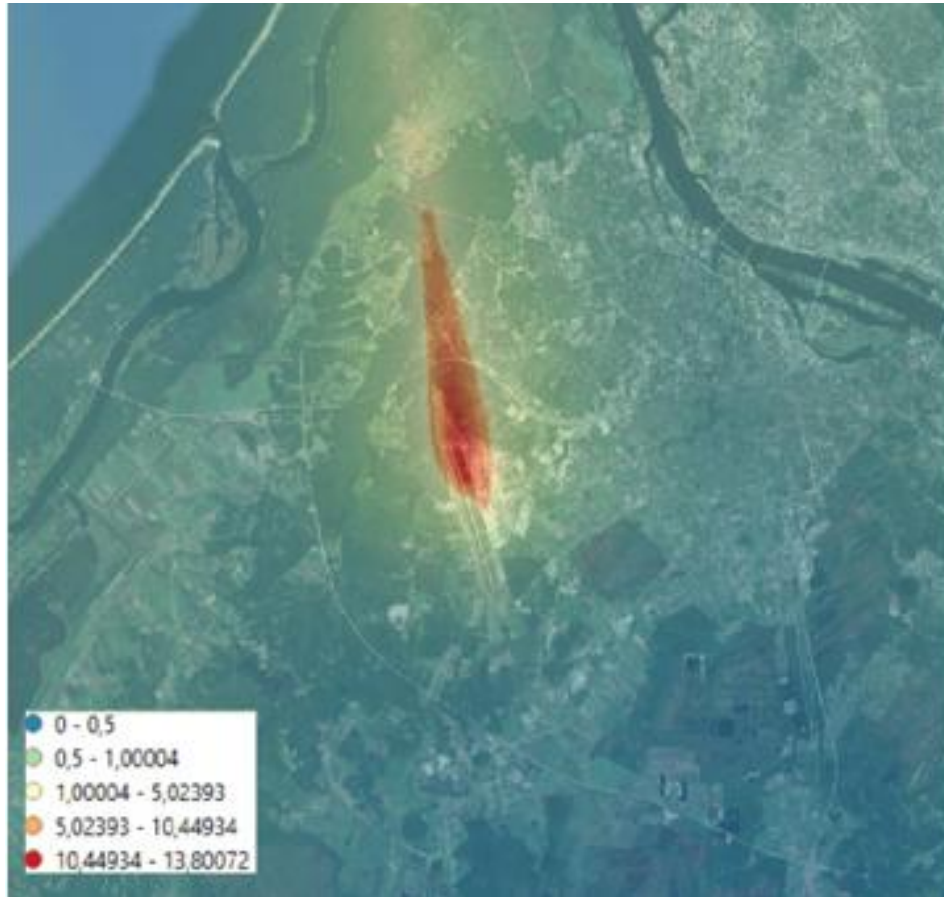


Figure 13 - Example of hourly dispersion of CO ($\mu\text{g}/\text{m}^3$) over Riga measured at 1.5-meter height

3.4. Corrector factor calculation (Delta)

This section describes a procedure for estimating the error affecting a POD-based reconstruction of a fluid dynamic field, when no reference high-fidelity simulation is available for the case of interest. The methodology is first illustrated in general terms, then applied to the LES/CRIDA correction factor estimation, where the LAQ field was calculated with Alya, the multi-physics code developed by BSC used to compute the LES simulations, and with a low-fidelity and much cheaper evaluation model, AERMOD, used by CRIDA.

Setup and notation

A set of n high-fidelity (LES) analyses is taken as ground truth. For each of them, the correction field is defined as the difference

$$\delta(x) = \text{LES}(x) - \text{model}(x)$$



between the LES result and the faster approximate model evaluated at the same point in the field. A POD analysis of the n snapshots of $\delta(x)$ yields a POD basis of n modes, ranked by decreasing energy content.

Goal and core problem

With this model, the approximate correction $\hat{\delta}(x)$ can be “estimated” for a case not included in the snapshots used to build the POD basis, without running the corresponding high-fidelity simulation.

For such a case, however, no matching LES run exists: the true $\delta(x)$ is unknown, and running LES only to check one estimate would defeat the purpose of the fast model. It is therefore necessary to estimate the error being made *indirectly*, from the training snapshots and from the reconstruction itself. Two stages are proposed: a qualitative screening and a quantitative confidence indicator.

3.4.1. Stage 1 — Qualitative screening

A very rough estimate can be obtained by considering which POD modes are actually used to reconstruct $\hat{\delta}$. The working hypothesis for assessing the quality of the approximation is the following: if the most heavily weighted components of the POD-reconstructed correction are low-energy modes, there is a very high probability that the reconstructed $\hat{\delta}$ corresponds to a case far from the snapshots used to compute the POD, and that the error committed is therefore high.

An initial qualitative assessment can thus be obtained simply by observing the weights used to build $\hat{\delta}$ from the POD modes:

- weights of the lowest-energy modes small $\rightarrow$ higher confidence in $\hat{\delta}$;
- weights of the lowest-energy modes large $\rightarrow$ the $\hat{\delta}$ estimate is to be considered unreliable.

3.4.2. Stage 2 — Quantitative confidence indicator

The next step is to estimate how far the reconstructed correction is from the actual value, that is, to construct a confidence interval. The following simplified procedure is proposed, built from the same POD reconstruction:

1. Compute $\hat{\delta}_f(x)$ using all the available POD modes (the subscript f indicates that the full set of modes is used).
2. Compute $\hat{\delta}_{-k}(x)$, excluding the k lowest-energy modes.



3. The correction is evaluated over the entire field, but for convenience a single (lumped) numerical value is needed. Various options are possible; the most straightforward one is the RMSE of the difference between the two reconstructions, evaluated over the N field points:

$$\hat{\Delta} = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\hat{\delta}_f(x_i) - \hat{\delta}_{-k}(x_i) \right)^2}$$

4. The resulting $\hat{\Delta}$ value is compared with the values obtained in the same way from the snapshots used to construct the POD. If $\hat{\Delta}$ lies significantly above the maximum of those values, the estimate can be assumed to be affected by a significant error.

3.4.3. Known limitation and leave-one-out validation

The methodology lacks a validation step, i.e., a verification against an LES analysis of the new case that would quantify the actual error. A mitigation is available through the leave-one-out technique on the existing snapshots: one snapshot is removed, the POD basis is rebuilt from the remaining ones, and the held-out case is reconstructed and screened with both the qualitative and quantitative procedures sketched above. Since the LES result of the held-out case is known, the comparison provides a genuine, if indirect, estimate of the real-world error of the method.

The workflow is reported for the sake of clarity in Figure 14. It is worth noting that the a_i weights in the reconstruction formula

$$\hat{\delta}(x) = \sum_{i=1}^N a_i \varphi_i(x)$$

can be obtained by a Gappy-POD technique by projecting the low-fidelity field values on the POD basis components φ_i .



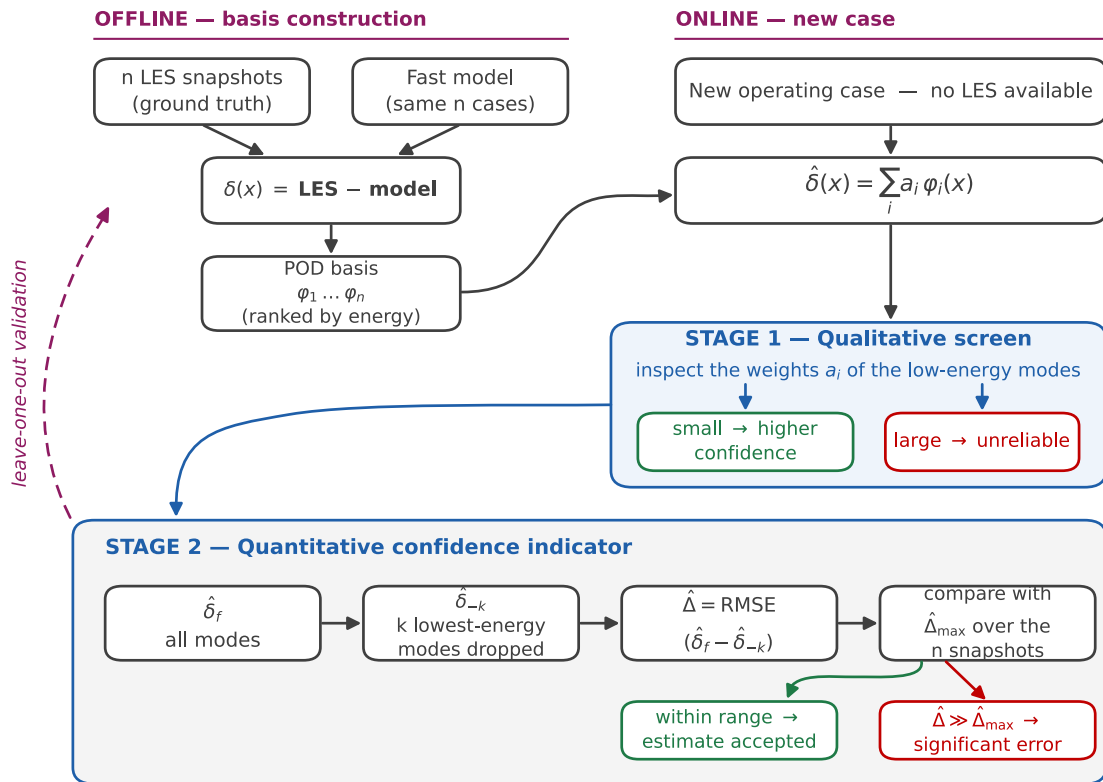


Figure 14: Schematic of the error estimation procedure: offline construction of the POD basis of $\delta(x)$, online reconstruction for a new case, qualitative screening (Stage 1), quantitative confidence indicator (Stage 2), and leave-one-out validation loop.

3.4.4. Application to the LES/AERMOD correction factor

Dataset and POD basis

The starting point is a POD analysis of 14 snapshots, yielding a POD basis of 14 modes. The POD is defined relative to the difference $\delta(x)$ between the BSC LES analyses (ground truth) and the approximate model AERMOD used by CRIDA, evaluated at each point of the field. Accordingly, $n = 14$ in the notation of the previous subsection.

Qualitative screening of a new case

For a case not included in the 14 LES simulations, inspect the 14 POD reconstruction weights as described. If the weights associated with the lowest-energy modes of the 14-mode basis are large, the reconstructed $\hat{\delta}$ is flagged as unreliable, and the quantitative check previously described may be used to quantitatively estimate the error.



Quantitative indicator

The procedure to estimate the quantitative indicator is applied with $k = 3$, i.e.:

- $\hat{\delta}_f(x)$ is computed using all 14 POD modes;
- $\hat{\delta}_{-3}(x)$ is computed excluding the three lowest-energy modes;
- the two fields are collapsed into the single RMSE value $\hat{\Delta}$.

Reference threshold

The reference threshold is determined by repeating the same computation for the 14 snapshots used to construct the POD, producing the reference population of $\hat{\Delta}$ values and, in particular, their maximum. A new case whose $\hat{\Delta}$ is significantly far from that maximum is assumed to carry a significant error.

Validation plan

No LES analysis is currently foreseen for the new cases, so the actual error cannot be measured directly. The leave-one-out exercise of the previous section can be carried out on the available dataset: 14 folds, each rebuilding the POD basis from 13 snapshots and reconstructing the excluded one, giving an indirect but quantitative measure of the accuracy of the estimate.

3.4.5. Application to low-fidelity scenarios

Algorithms for data fusion and methodology for applying the delta correction factors (including interpolation and extrapolation technique) are described in D6.1 [1].

The resulting concentration-change field is produced separately for each pollutant, receptor, assessment period, and scenario. It is then combined with the baseline concentration obtained from the dispersion model.

The final concentration is calculated by adding the estimated concentration change to the baseline concentration:

$$\text{final concentration} = \text{AERMOD concentration} + \text{estimated delta}$$

The AERMOD input files are adjusted to generate different output plotfiles (PLT) for each aircraft. These files contain the results for different groups of segments that belong to a same aircraft trajectory.



Each PLT has their associated conditions, in terms of wind direction, wind velocity, and mass flow. Once the deltas are calculated, they are added to the concentration field in the PLT file by replacing the initial value (calculated by AERMOD) by the corrected one.

All these results are aggregated and metrics and KPIs (average hourly concentrations, daily concentrations, etc.) calculated for the whole scenario. **It is important to remark that results presented in section 5 of this document already have this correction factor applied.**

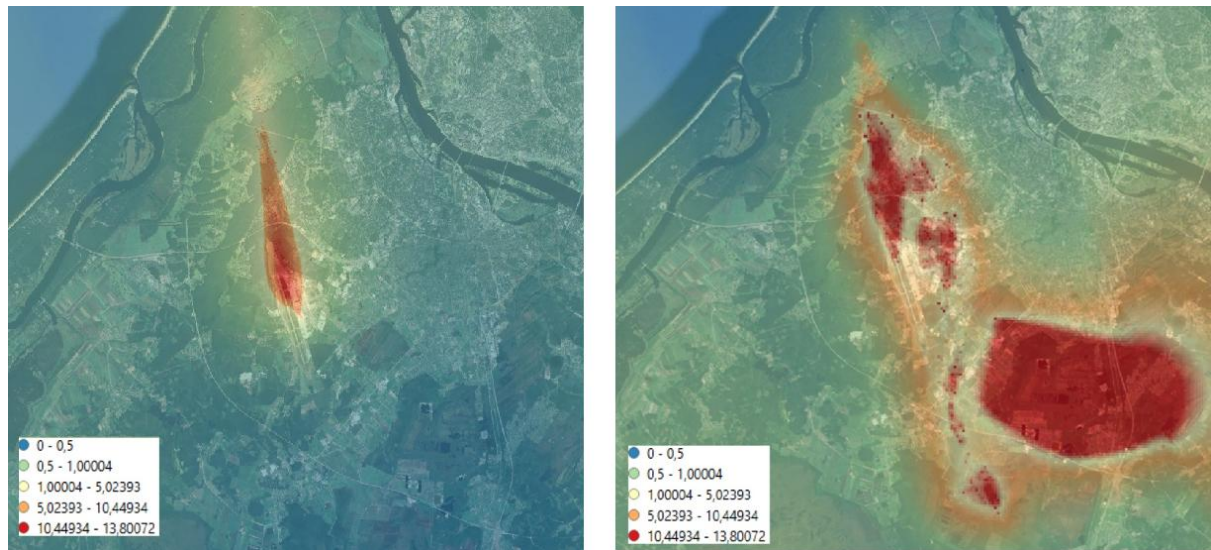


Figure 15. Comparison between initial resulted concentrations of CO ($\mu\text{g}/\text{m}^3$) (left) and concentrations after deltas application (right) at RIX

3.5. Noise calculation

3.5.1. High-fidelity calculations

Numerical simulations for noise assessment on INDIGO aircraft

For the noise assessment of the INDIGO aircraft, two simulations along the trajectory identified for validation of the hybrid Reynolds Averaged Navier Stokes- Computational Aeroacoustics (RANS-CAA) approach [4] with RIX data in WP6 were considered, for a reference operating point and the most promising noise-optimized operating condition provided by UC3M. The trajectory considered is the one described in Figure 16, that consists of two main segments (blue and cyan-colored segments), excluding ground roll (red-colored segment).



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Trajectory Segment	Altitude [ft]	Gradient [%]	Vertical [ft/min]	Speed
Blue	0 - 1000	17.4	2562	
Cyan	1000 - 3000	14.9	2220	

Table 7: RIX trajectory segments description

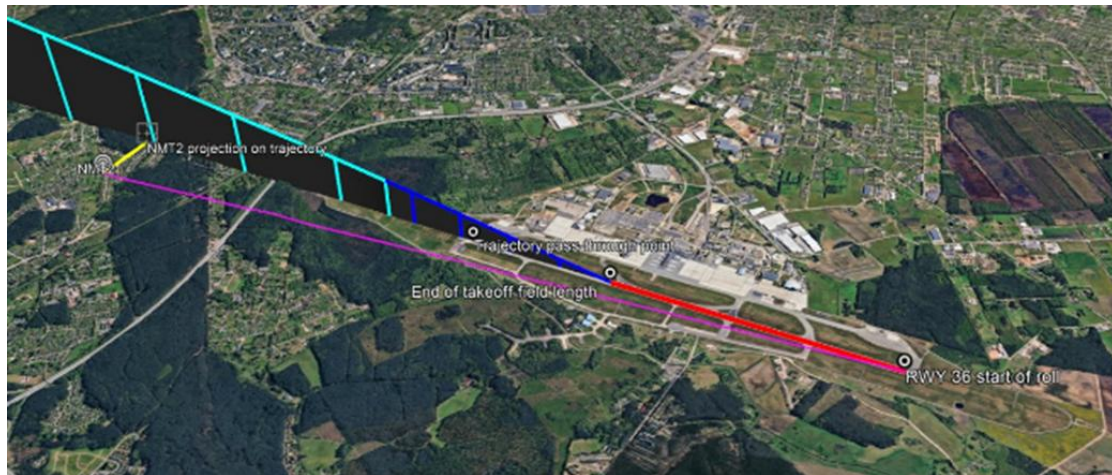


Figure 16: INDIGO aircraft RIX trajectory description. The fuchsia line represents the segment from the mic to the start of the trajectory.

A preliminary assessment with IMMIS+ was conducted, to select the most representative point of the trajectory (longer-lasting engine condition) for the corresponding CAA simulation, for which the mid-points of the blue-colored and cyan-colored segment were considered to be flown along the full trajectory to compute the EPN levels the microphone located at the lateral location 'NMT2'.

Using the available analytical source models of IMMIS+, the selected approach of the mid-to-high-fidelity data trained surrogate approach [5] can be estimated to produce prediction errors of less than 0.5 EPNLdB for the entire flight trajectory, as could be observed for the cyan-colored segment. Based on these findings, the reference aircraft operational parameters for the CAA simulation eventually were selected from the midpoint of the cyan-colored segment. This selection may be further justified by taking into account that this segment is the one in which the aircraft actually passes over the selected microphone position. The aircraft operational parameters for the reference point are summarized in table below.



Altitude [m]	True Air Speed [m/s]	Air Density [kg/m ³]	Temperature [K]	Flight Path Angle [°]	Angle of Attack [°]	Air Speed of Sound [m/s]
602.4	76.52	1.15	284.23	8.47	10.59	338.54
Powertrain Thrust [N]	Inboard Propeller Thrust [N]	Outboard Propeller Thrust [N]	Inboard Propeller Tip Mach nr.	Outboard Propeller Tip Mach nr.	Inboard Propeller RPM	Outboard Propeller RPM
151002.8	23757.3	12936.01	0.39	0.4	518	660.92

Table 8: Aircraft operational parameters of reference operating point

The aircraft operational parameters for the noise-optimized operating condition are included in table below.

Altitude [m]	True Air Speed [m/s]	Air Density [kg/m ³]	Temperature [K]	Flight Path Angle [°]	Angle of Attack [°]	Air Speed of Sound [m/s]
602.40	76.52	1.15	284.23	8.47	10.17	338.55
Powertrain Thrust [N]	Inboard Propeller Thrust [N]	Outboard Propeller Thrust [N]	Inboard Propeller Tip Mach nr.	Outboard Propeller Tip Mach nr.	Inboard Propeller RPM	Outboard Propeller RPM
146482.04	21911.63	12832.35	0.37	0.4	486.31	643.83

Table 9: Aircraft operational parameters of noise-optimized operating condition

The comparison of the INDIGO aircraft simulated results at the NTM2 microphone was performed in terms of Sound Exposure Level (LAE), with a recorded A-Weighted value of 83,3 dBA corresponding to the most frequent Airbus A320 RIX trajectory. Two CAA simulations were considered, comparing the reference operating point and the most promising noise-optimized operating condition provided by UC3M.

In Figure 17 and Figure 18, the results are shown in terms of pressure fluctuation contour plots. No clear change in pressure fluctuations can be highlighted.



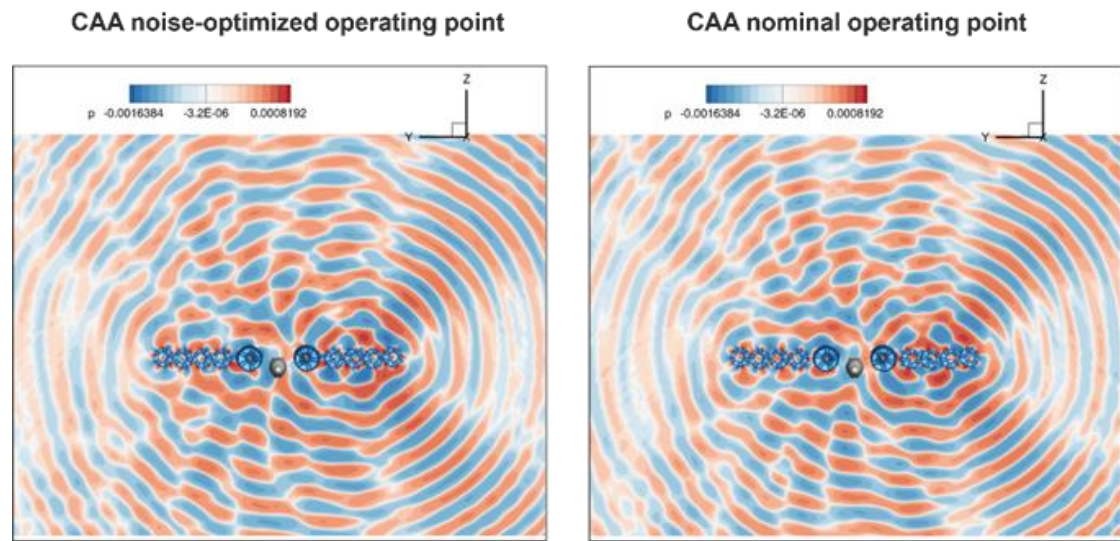


Figure 17: INDIGO aircraft results in terms of pressure fluctuations contour plots, for the plane located at the outboard propellers

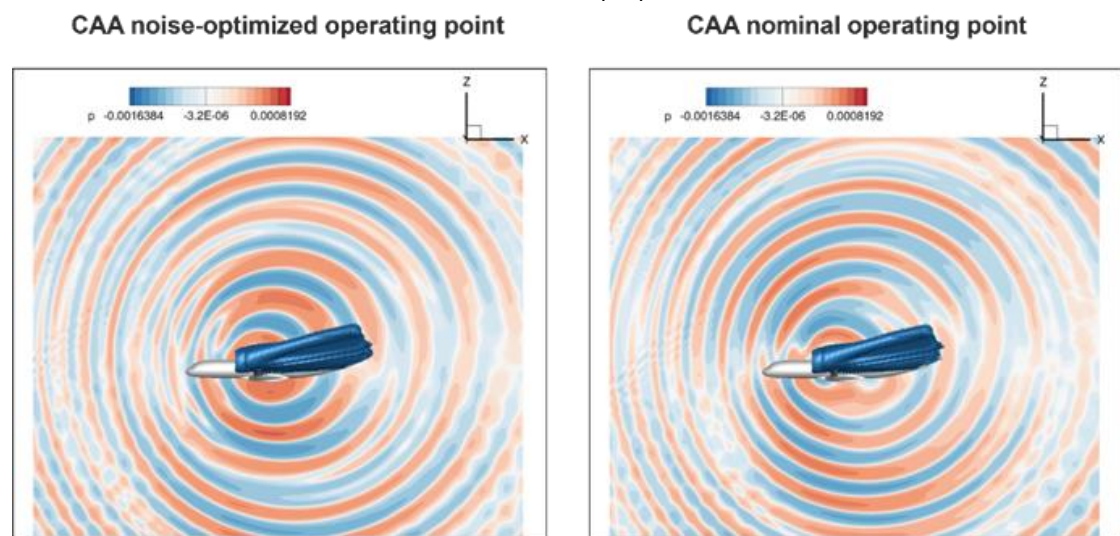


Figure 18: INDIGO aircraft results in terms of pressure fluctuations contour plots, for the plane located at the middle of the aircraft fuselage

Figure 19 and Figure 20 show for the 1st Blade Passing Frequency (BPF) of the installed outboard propellers the resulting directivity by means of the change in SPL recorded on the far-field hemispheres and rescaled to a distance of 30 m (aircraft near-field). Such prepared hemisphere data serves as the main input for the fly-over tool IMMIS+. The figures show on the left results for noise-optimized operating point and the nominal operating point results on the right.



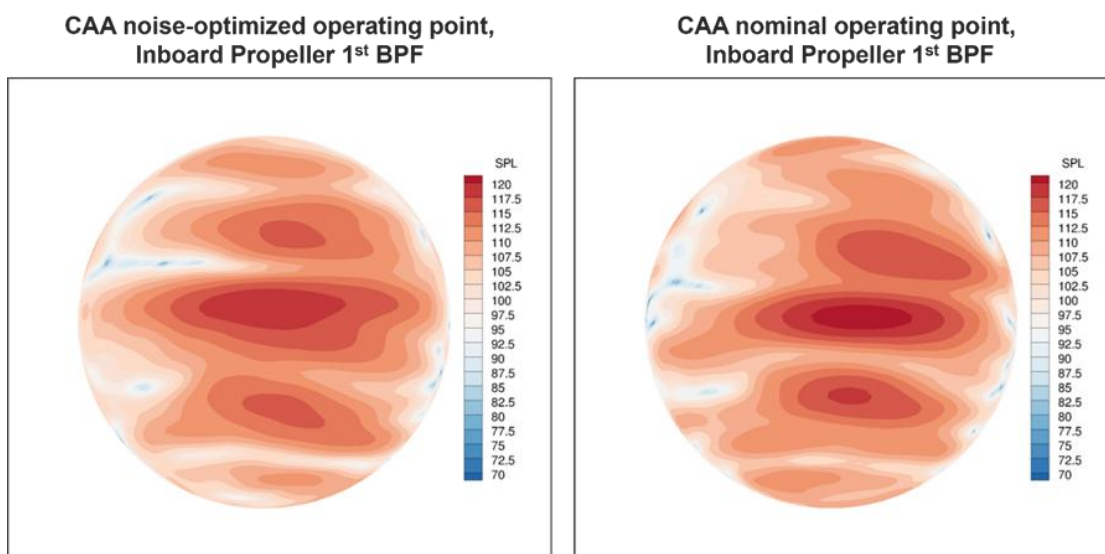


Figure 19: INDIGO aircraft results, contour plots of the 1st BPF of the inboard propellers on the hemisphere used in the fly-over tool IMMIS+

The figures confirm no clear change in SPL between the 2 operating points considered for the 1st BPF of the outboard propellers. For the inboard propellers, a slight reduction in Sound Pressure Level (SPL) can be seen for the noise-optimized operating point.

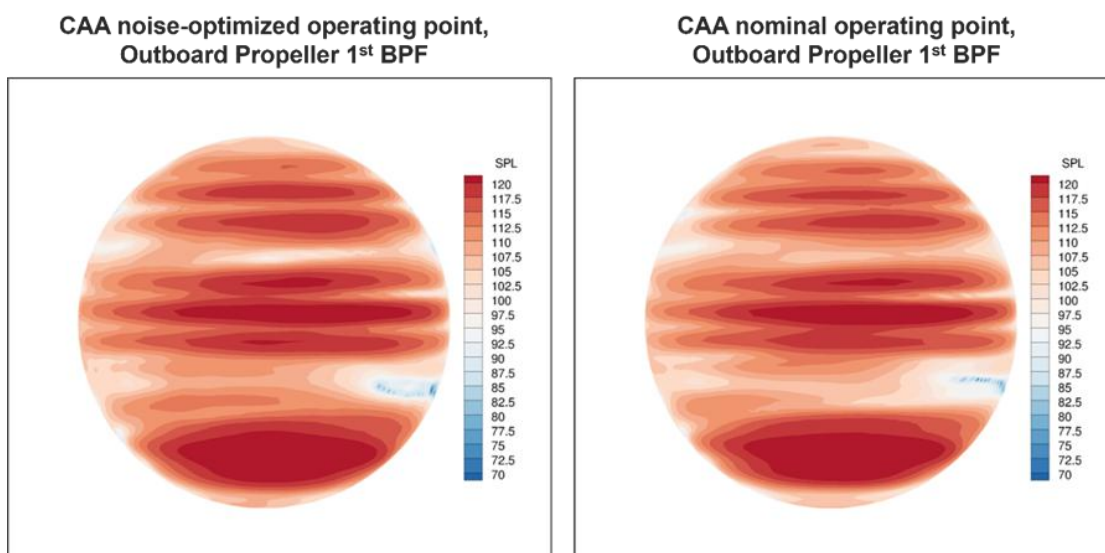


Figure 20: INDIGO aircraft results, contour plots of the 1st BPF of the outboard propellers on the hemisphere used in the fly-over tool IMMIS+

The corresponding LAE levels resulting from the fly-over trajectory for both operating points show a reduction of 6 dBA compared to the reference A320 flight from RIX database.



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The comparison in terms of LAE was performed so far only including the propeller tonal noise component. For a more realistic noise assessment, the inclusion of broadband noise in the overall assessment was considered based on knowledge acquired over the past decades at DLR. For take-off operational conditions, the contribution to broadband noise due to landing gears is typically greater than approximately 3 dB with respect to other aircraft broadband noise type of sources, therefore only the inclusion of such a broadband noise contribution was considered within INDIGO [6]. For landing gears noise estimation, DLR in-house semi-empirical prediction tool PROFAN was used, summing the results energetically to the results obtained from the propeller tonal noise assessment. Only a preliminary estimation could be performed, since no landing gear design was considered within the scope of the INDIGO project. A traditional three-landing-gears design was considered, with one nose landing gear and two main landing gears, based on Airbus A320 landing gears.

The sizing of the main landing gears was chosen as follows:

- Number of wheels = 2
- Wheel width = 0.41144 m
- Wheel diameter = 1.21107 m
- Length single strut = 2.15610 m
- Diameter single strut = 0.20831 m

The sizing of the nose landing gear was chosen as follows:

- Number of wheels = 2
- Wheel width = 0.2098 m
- Wheel diameter = 0.7152 m
- Length single strut = 1.5909 m
- Diameter single strut = 0.1716 m

Since the trajectory considered is representative of a take-off and early climb procedure, it was considered in the IMMIS+ evaluation that the landing gears would be retracted after an altitude of 15 m. The addition of the landing gear evaluation contributed to an increase of 0.5 dbA in the levels detected for the propellers-only evaluation.

3.5.2. Low-fidelity calculations

The noise assessment has been carried out using the spherical wave propagation formulas. The source emits power (W). For every distance 'r', the power 'flows' outwards from the sphere of radius 'r', passing through an area of $4\pi r^2$.

The power is therefore distributed in proportion to the increase in distance. The area increases with the square of 'r', so the intensity (W/S) decreases with the square of 'r':



$$I(r) = \left(\frac{\text{power}}{\text{area}}\right) = \frac{W}{4\pi r^2} = \frac{p_{eff}^2}{\rho c} \Rightarrow Li = Lp = 10 * \log_{10} \left(\frac{W/4\pi r^2}{I_0}\right) \rightarrow$$

$$\frac{p_0^2}{\rho c} \sim I_0 = W_0 \Rightarrow Li = Lp = 10 * \log_{10} \left(\frac{W/4\pi r^2}{W_0}\right) = 10 * \log_{10} \left(\frac{W}{W_0}\right) + 10 * \log_{10} \left(\frac{1}{4\pi r^2}\right) \rightarrow$$

$$Lp = Lw - 20 * \log_{10}(r) - 10 * \log_{10}(4\pi) \rightarrow$$

$$Lp = Lw - 20 * \log(r) - 11 \text{ dB}$$

For simplicity, ambient attenuation is assumed to be zero and the source, for INDIGO aircraft, is characterised as omnidirectional (as this data is not available).

Sound power level (Lw) data from INDIGO is provided by the high-fidelity calculations (see section 3.5.1). Conventional aircraft data related to Lw is obtained from the Aircraft Noise and Performance (ANP) database from EASA [7].

The developed model divides each trajectory into different segments. For each of these, a sound pressure level (Lp) is calculated by associating it with the minimum distance to each of the receptors.

As some receptors are receiving Lp from different trajectories at the same time, a resulting Lp is calculated as a logarithmic sum. Their associated duration ' Δt ' is also taken into consideration in order to ponderate their contribution to the final hourly result (LpF):

$$LpF = 10 * \log_{10} \left(\frac{\Delta t(\text{segment}(1)) * 10^{\frac{Lp(S1)}{10}} + \Delta t(\text{segment}(2)) * 10^{\frac{Lp(S2)}{10}} + \dots + \Delta t(\text{segment}(n)) * 10^{\frac{Lp(Sn)}{10}}}{3600} \right)$$

The A-weighted average sound level (LAeq) is calculated for three time periods, with their corresponding penalties:

- ✓ Day (07:00-19:00): No penalty (0 dB added)
- ✓ Evening (19:00-23:00): +5dB penalty added.
- ✓ Night (23:00-07:00): +10dB penalty added.

LDEN (Day-Evening-Night Level) is obtained from the following formula:

$$L_{DEN} = 10 * \log_{10} \left[\frac{12}{24} * 10^{\frac{L_{day}}{10}} + \frac{4}{24} * 10^{\frac{L_{evening}+5}{10}} + \frac{8}{24} * 10^{\frac{L_{night}+10}{10}} \right]$$

Night is additionally calculated separately and independently in order to be used as an indicator for their derived impact on human health (see section 6.1.1.4).



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3.6. Health and economic impact methodology

The health and economic impact assessment developed within INDIGO aims to quantify the potential societal benefits associated with the introduction of the INDIGO aircraft concept by translating changes in environmental exposure into measurable health outcomes and, subsequently, into economic values.

The methodology follows an impact-pathway approach, whereby changes in aircraft technology and fleet composition affect aircraft emissions, which in turn modify ambient pollutant concentrations in the areas surrounding the airports. These concentration changes determine variations in population exposure and may consequently result in changes in the incidence of adverse health outcomes. The resulting health effects can finally be expressed in monetary terms, providing a common metric for comparing the benefits associated with the different INDIGO scenarios.

For local air quality (LAQ), health impacts are quantified using the *Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE)*, an open-source health impact assessment tool developed by the United States Environmental Protection Agency (U.S. EPA). BenMAP-CE is designed to estimate the public-health consequences and associated economic value resulting from changes in ambient air-pollution concentrations [8].

BenMAP-CE provides the methodological link between externally generated air-quality concentration data and their expected effects on the exposed population. Within the INDIGO assessment chain, pollutant concentration fields are therefore first generated through the LAQ modelling process and subsequently processed and imported into BenMAP-CE. The software combines the resulting changes in pollutant concentrations with spatially resolved population data, baseline health incidence rates, and concentration-response functions (CRFs) derived from epidemiological literature.

Within INDIGO, BenMAP-CE is primarily used as a scenario-comparison tool. For each airport case study, a reference scenario representing conventional aircraft operations is compared with the corresponding INDIGO scenario, representing different levels of replacement of conventional aircraft with hybrid-electric aircraft (i.e. 10%, 20%, 30% and 40%, corresponding to SOL10, SOL20, SOL30 and SOL40, respectively).

Consequently, the assessment does not aim to quantify the total health burden attributable to air pollution around each airport. Instead, it estimates the incremental health benefit attributable specifically to the transition from the reference configuration to the INDIGO scenario.

A common methodological framework is applied across the four airport case studies to ensure comparability of the resulting indicators. Airport-specific characteristics, including



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the spatial assessment domain, population distribution, mortality rates and baseline health statistics, are nevertheless retained in the analysis to adequately represent local exposure and demographic conditions.

3.6.1. Health impact assessment from LAQ and noise

3.6.1.1. General approach and impact-pathway framework

As mentioned before, the health impact assessment associated with local air quality is performed using BenMAP-CE, following a scenario-comparison approach.

The assessment consists of four main components:

1. Preparation of the air-quality concentration data;
2. Definition of the exposed population;
3. Definition of baseline mortality rates for the selected health endpoints;
4. Application of concentration-response functions to estimate changes in health outcomes.

These components are combined within BenMAP-CE to estimate the number of avoided or additional health cases associated with the modelled change in pollutant concentrations.

The assessment therefore quantifies incremental health impacts, rather than the total health burden associated with air pollution. In other words, the results represent the health benefit attributable specifically to the change from the reference fleet to the corresponding INDIGO scenario.

3.6.1.2. Air quality input data and processing pipeline

The starting point of the LAQ health assessment is the set of pollutant concentration outputs produced by the atmospheric dispersion modelling for the reference and INDIGO scenarios.

The pollutants considered within the INDIGO modelling framework include, depending on the availability and characteristics of the individual case study, nitrogen oxides (NO_x), particulate matter (PM), black carbon (BC), carbon monoxide (CO) and volatile organic compounds/hydrocarbons (VOC/HC).

Since BenMAP-CE requires air-quality information to follow a predefined Model Data structure, the raw dispersion-model outputs are processed through a dedicated Python-based data-processing pipeline. This processing stage converts the original concentration outputs into a format compatible with BenMAP-CE and performs the temporal and spatial aggregation required for the corresponding pollutant and exposure metric.

The same processing procedure is systematically applied to both the reference and INDIGO scenarios. This is essential to ensure that the calculated concentration difference is attributable to changes in aircraft emissions and operations rather than to inconsistencies in data treatment.



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Following processing, the reference and INDIGO concentration surfaces are imported into BenMAP-CE as the two air-quality scenarios to be compared. Their difference, ΔC , constitutes the fundamental exposure-change variable used in the subsequent health-impact calculation.

3.6.1.3. Study area and spatial assessment framework

The spatial domain of the health impact assessment is defined individually for each airport according to the extent of the LAQ modelling domain and the availability of population and health data.

Although the same methodological framework is applied to all INDIGO case studies, the spatial discretization does not necessarily have to be identical across airports. Depending on the underlying dispersion model, geographical data and available demographic information, concentration and population information may be represented through receptor grids, regular analysis grids or appropriate geographical or administrative units.

The fundamental methodological requirement is the establishment of a consistent spatial relationship between exposed population, baseline health data and air-quality concentrations.

Concentration data are therefore spatially associated with the population information corresponding to the same analysis unit. This enables BenMAP-CE to account for the spatial heterogeneity of both pollution exposure and population distribution.

This spatially resolved approach is particularly important in airport-related assessments. The magnitude of a health benefit is not determined exclusively by the magnitude of the concentration reduction. A relatively large concentration reduction occurring in a sparsely populated area may produce a smaller overall health benefit than a more moderate concentration reduction affecting a densely populated area.

3.6.1.4. Population and demographic data

Population data represent the exposed population to which the modelled concentration changes are applied. Spatially resolved population datasets are therefore incorporated into BenMAP-CE for each case study and associated with the corresponding analysis grid or geographical units.

Where required by the selected CRFs, population information is differentiated according to age group. This is necessary because epidemiological functions are frequently defined for specific population groups. For example, some mortality functions apply only to the adult population above a specified age.

The demographic structure implemented in BenMAP-CE is therefore aligned with the population groups for which the epidemiological evidence is valid. This prevents the application of a CRF to population groups outside the age range considered in the underlying study.



Population data are processed using a consistent methodology across the case studies, while retaining the local demographic characteristics of each study area. This ensures that differences in estimated health impacts between airports reflect not only differences in concentration changes but also differences in the size and spatial distribution of the exposed population.

The data were obtained from official national, regional or municipal statistical sources. Preference was given to the most recent datasets available at a spatial resolution compatible with the geographical units adopted for each case study. Table below reports the source, reference year and spatial resolution of the population dataset used for each airport.

Airport case study	Reference year	Spatial resolution	Dataset reference
Barcelona	2023	District	Barcelona Open Data [9]
Dortmund	2023	District	Dortmund Open Data Portal [10]
Madrid	2023	District	Geoportal Madrid [11]
Riga	2023	Neighbourhood	Official Statistics Portal of Latvia [12]

Table 10: Sources, reference years and spatial resolution of the population datasets used in the INDIGO health impact assessment

It should be noted that the population datasets considered in the assessment are restricted to the administrative boundaries of the respective cities and do not include the wider metropolitan areas. Consequently, populations residing outside the selected city boundaries are not represented in the health-impact assessment, even where they may be located relatively close to the airport or potentially affected by airport-related emissions. This geographical limitation is particularly relevant for airports located outside or close to the boundary of the corresponding municipality, such as Barcelona Airport, where part of the surrounding potentially exposed population falls outside the study area. The geographical extent of the population dataset should therefore be considered when interpreting and comparing the estimated health benefits across the four case studies.

To support the interpretation of the health-impact results, Figure 21 presents the spatial distribution of population density across the four airport case studies.



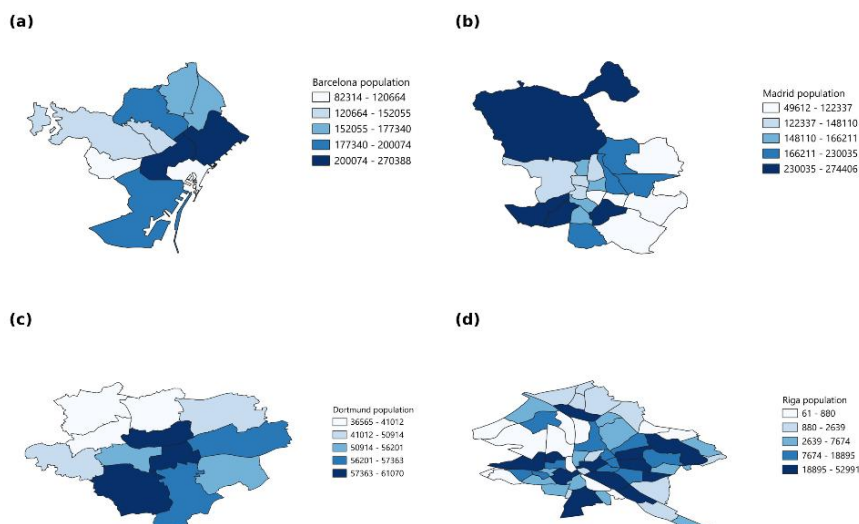


Figure 21 – Population distribution across the administrative areas considered in the four case studies: (a) Barcelona districts; (b) Madrid districts; (c) Dortmund districts; and (d) Riga neighbourhoods

Population density constitutes a key determinant of the estimated health benefits because the concentration changes calculated for each analysis unit are applied to the population residing within that unit. Consequently, comparable reductions in pollutant concentrations may result in substantially different health impacts depending on the number and spatial distribution of people exposed.

Areas characterized by both relatively high population density and substantial reductions in pollutant concentrations are generally expected to contribute more strongly to the estimated number of avoided health cases. Conversely, even comparatively large concentration reductions may produce limited health benefits when they occur over sparsely populated areas. The population-density maps therefore provide essential contextual information for interpreting differences in the estimated avoided premature deaths and other health outcomes across Madrid, Barcelona, Dortmund and Riga.

Nevertheless, population density alone does not determine the final health impact. The results also depend on the magnitude and spatial distribution of the concentration change, the age structure of the exposed population, the baseline incidence rate and the concentration-response function applied.



3.6.1.5. Baseline health incidence data

Baseline mortality incidence represents the underlying frequency of mortality in the population before accounting for the change in pollutant exposure associated with the INDIGO scenario.

For each case study, baseline mortality incidence rates are obtained, whenever possible, from official national, regional or local health and statistical databases. Priority is given to data that are geographically representative of the population included in the corresponding assessment.

Baseline mortality data are matched to the definition of the mortality endpoint used by the selected concentration-response function (CRF). Consistency is required in terms of mortality category, age range and, where applicable, coding of health outcome.

For all four INDIGO case studies, the baseline mortality rate was available at city level and was therefore applied uniformly to all the smaller spatial units included within the corresponding urban area.

The sources, reference years and geographical resolution of the baseline mortality data used for each case study are summarized in table below.

Case study	Geographical level of the source data	Reference year	Data source
Barcelona	City level	2023	Agència de Salut Pública [13]
Dortmund	City level	2023	Information und Technik Nordrhein-Westfalen [14]
Madrid	City level	2023	INE (Instituto Nacional de Estadística) [15]
Riga	City level	2023	Official Statistics Portal of Latvia [12]

Table 11: Sources, reference years and spatial resolution of the baseline mortality data used in the INDIGO health impact assessment

3.6.1.6. Selection and application of concentration-response functions

Concentration-response functions provide the quantitative relationship between a change in pollutant exposure and the corresponding change in the risk of a specific health outcome. The selection of appropriate CRFs therefore constitutes one of the most important components of the health impact assessment.

For INDIGO, CRFs were selected from recent peer-reviewed epidemiological literature, with priority given to systematic reviews, meta-analyses and large European cohort studies considered suitable for quantitative Health Risk Assessment (HRA).



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Attention was given to evidence developed within, or directly relevant to, the WHO Health Risks of Air Pollution in Europe (HRAPIE) framework, including the evidence considered in the HRAPIE-2 update. Large European studies examining the health effects of relatively low ambient pollutant concentrations were also considered particularly relevant because of their applicability to the European airport environments assessed within INDIGO.

Importantly, not all CRFs included in the assessment are assigned the same evidential weight. A distinction is made between primary CRFs, used as the principal basis for interpretation and graphical presentation of the INDIGO results, and complementary CRFs, used to investigate additional endpoints, characterize epidemiological uncertainty or perform sensitivity analyses.

This prioritization is established based on the quality, consistency and applicability of the epidemiological evidence, rather than on the magnitude of the health benefit subsequently estimated. This approach avoids selectively emphasizing concentration–response functions (CRFs) that produce larger health benefits and ensures that the principal INDIGO conclusions are driven by the robustness and relevance of the underlying epidemiological evidence.

For long-term particulate-matter-related mortality, particular priority is assigned to Orellano et al. (2024). This study updates the systematic review and meta-analysis conducted to support the WHO Global Air Quality Guidelines and evaluates the association between long-term exposure to PM_{2.5} and PM₁₀ and all-cause and cause-specific mortality. The updated meta-analysis included 106 studies and reported positive associations for nearly all investigated exposure–outcome pairs, with the certainty of evidence rated as high for the majority of them. The resulting PM mortality functions are therefore treated as primary CRFs within INDIGO, with all-cause mortality used as one of the principal health indicators. [16]

For long-term NO₂-related mortality, *Kasdagli et al.* (2024) is considered a primary epidemiological reference. The study provides an updated systematic review and meta-analysis of the evidence linking long-term NO₂ exposure with mortality, building upon the evidence base considered for the WHO Air Quality Guidelines. Since the air-quality modelling performed within INDIGO provides concentrations for total NO_x rather than NO₂ separately, the NO₂-based concentration–response functions are applied to changes in modelled NO_x concentrations. This methodological choice is based on the assumption described in Section 1, whereby changes in NO_x are used as a proxy for changes in NO₂ exposure, and should be considered when interpreting the resulting health-impact estimates. [17]

Particular relevance is also assigned to *Stafoggia et al.* (2022) within the *Effects of Low-Level Air Pollution: A Study in Europe* (ELAPSE) project. The study analysed more than 28 million participants from seven large European cohorts and investigated long-term exposure to PM_{2.5}, NO₂ and black carbon (BC), including exposures at comparatively low ambient concentrations. Positive associations were identified between these pollutants and non-accidental mortality, with analyses also covering cardiovascular, non-malignant respiratory and lung cancer mortality. Importantly for INDIGO, associations were also observed at pollutant concentrations below established air-quality guideline or limit values. ELAPSE-derived functions are therefore considered high-relevance European evidence and are used to complement the primary CRFs and assess the consistency and robustness of the estimated health benefits [18].



So et al. (2022) provides additional European evidence based on a nationwide Danish cohort of approximately 3.1 million individuals. The study examined long-term exposure to PM_{2.5}, NO₂ and BC and its association with natural and cause-specific mortality, thereby providing complementary evidence on the health effects of pollutants particularly relevant to combustion and traffic-related emissions. [19]

Within INDIGO, the corresponding CRFs are therefore used primarily as supporting and sensitivity functions, allowing the results obtained from the primary epidemiological references to be compared against an additional large European population-based study.

The overall prioritization adopted for the INDIGO assessment is summarized in table below.

<i>Epidemiological source</i>	<i>Pollutant(s)</i>	<i>Principal health outcomes</i>	<i>Evidence relevance</i>	<i>Role in INDIGO</i>
<i>Orellano et al. (2024)</i>	PM _{2.5}	All-cause and cause-specific mortality	Strong updated systematic review/meta-analytical evidence	Primary – main PM mortality results and figures
<i>Kasdagli et al. (2024)</i>	NO ₂	All-cause and cause-specific mortality	Updated evidence; certainty depends on endpoint	Primary – main NO₂ mortality results
<i>Stafoggia et al. (2022), elapse</i>	PM _{2.5} , NO ₂	Natural/non-accidental and cause-specific mortality	Large european evidence base; particularly relevant at low concentrations	High-relevance european evidence
<i>So & andersen et al. (2022)</i>	PM _{2.5} , NO ₂	Natural-cause and cause-specific mortality	Complementary european evidence	Supporting / sensitivity

Table 12: Epidemiological evidence and concentration–response functions selected for the INDIGO Health Impact Assessment

Based on this hierarchy, the main graphical representation of the INDIGO health results focuses preferentially on the CRFs supported by the strongest and most directly applicable evidence. Complementary functions are nevertheless retained to evaluate whether the direction and approximate magnitude of the estimated impacts remain consistent under alternative epidemiological assumptions.

For each selected CRF, the relative risk reported in the epidemiological study is converted, where necessary, into a concentration-response coefficient according to:

$$\beta = \frac{\ln(RR)}{\Delta C_{RR}}$$

where RR is the relative risk reported by the epidemiological study and ΔC_{RR} is the concentration increment associated with that relative risk.

BenMAP-CE subsequently combines the concentration-response coefficient with the change in concentration, exposed population and baseline incidence rate. The health-impact function can be expressed conceptually as:

$$\Delta Y = Y_0 \times Pop \times (1 - e^{-\beta \Delta C})$$



where:

- ΔY is the estimated change in the number of health cases;
- Y_0 is the baseline incidence rate;
- Pop is the exposed population;
- β is the concentration-response coefficient; and
- ΔC is the change in pollutant concentration between the reference and INDIGO scenarios.

A reduction in pollutant exposure therefore results in avoided adverse health outcomes, whereas an increase may result in additional cases.

Figure 22 illustrates the general health impact assessment framework applied in BenMAP-CE. Changes in pollutant concentrations are spatially combined with the exposed population and baseline incidence data, and the selected concentration–response functions are subsequently applied to estimate the resulting health impacts.



Figure 22 – Conceptual framework for estimating health impacts from changes in pollutant concentrations using BenMAP-CE. Source: EPA

3.6.1.7. Noise-related health impacts

Impacts on population have been estimated by following the World Health Organization (WHO) published Environmental Noise Guidelines for the European Region [20].

These guidelines contain studies on human health and other perceptions (such as annoyance) after their exposure to certain levels of noise emitted from different means of transport and other sources (road traffic, railway, wind turbines, leisure, aircraft, etc.).

This project has taken into consideration the studies related to aircraft noise. For average noise exposure, the guidelines recommend reducing noise levels produced by aircraft below 45 dB LDEN as aircraft noise above this level is associated with adverse health effects.

For night noise exposure, the recommendation is to reduce noise levels below 40 dB Lnight as aircraft noise is associated with adverse effects on sleep above this level.

The percentage of annoyance on population (%HA) is estimated with regard to these levels:



L_{den} (dB)	%HA
40	1.2
45	9.4
50	17.9
55	26.7
60	36.0
65	45.5
70	55.5

Table 13: Association between exposure to aircraft noise (LDEN) and annoyance (%HA). Source: WHO

On the other hand, the correlation between exposure to aircraft noise (L_{night}) and the percentage of sleep disturbance (%HSD) is also provided:

L_{night}	%HSD	95% CI
40	11.3	4.72–17.81
45	15.0	6.95–23.08
50	19.7	9.87–29.60
55	25.5	13.57–37.41
60	32.3	18.15–46.36
65	40.0	23.65–56.05

Table 14: Association between night exposure to aircraft noise (L_{night}) and sleep disturbance (%HSD). Source: WHO

3.6.2. Economic calculation from LAQ

The economic assessment represents the final stage of the LAQ impact pathway and converts the physical health impacts estimated through BenMAP-CE into monetary values.

Economic valuation provides a common metric through which the societal significance of the estimated health benefits can be interpreted and compared across INDIGO scenarios and airport case studies. The calculation is performed on the minimising health impact associated with each INDIGO scenario relative to the corresponding reference configuration.

For mortality-related impacts, the principal economic indicator is the monetary value associated with the reduction in premature mortality. The calculation therefore combines the estimated number of avoided premature deaths with an appropriate economic valuation coefficient.

3.6.2.1. Value of a Statistical Life

Mortality-related health benefits are monetized using the Value of a Statistical Life (VSL) approach.

VSL represents the aggregate willingness to pay for reductions in mortality risk that, across a sufficiently large population, correspond statistically to one avoided premature death.



For the INDIGO assessment, the conceptual interpretation of the VSL follows the mortality-risk valuation framework commonly applied in environmental benefit–cost analysis, including the approach described by the U.S. Environmental Protection Agency (EPA). For the quantitative economic assessment, however, the VSL values actually applied in the calculations are derived following the methodology developed by the OECD Environment Directorate (OECD-ENV), as described in detail in Chapter 7.

3.6.2.2. Calculation and interpretation of economic benefits

For mortality, the economic benefit associated with an INDIGO scenario can be expressed as:

$$B_{mortality} = \Delta Mortality \times VSL$$

where $B_{mortality}$ is the monetised mortality benefit and $\Delta Mortality$ represents the number of premature deaths avoided relative to the reference scenario.

Accordingly, a reduction in pollutant exposure that results in avoided premature mortality generates a positive economic benefit.

As with physical health assessment, particular care is required when aggregating economic values across pollutants and epidemiological functions. Monetary values derived from health estimates referring to overlapping endpoints cannot automatically be summed. Doing so would monetize the same underlying health effect more than once and would therefore overestimate the total economic benefit.



4. Sensitivity analysis

A sensitivity study based on the Use Cases' scenarios will be done to explore the impact of the margins of improvement of low-TRL technologies (e.g. battery weight or wing aspect ratio or noise mitigation techniques) on the LAQN KPIs of the selected airports for the nominal optimal DHEP-LARW aircraft incorporating the effects of weather conditions.

4.1. Design of experiments (DoE) over DHEP-LARW technologies

An aircraft-level optimization campaign was carried out to assess the influence of battery specific energy on the optimal aircraft design and mission performance. Three battery specific energy values were considered, namely 400, 600, and 800 Wh/kg, corresponding respectively to the Conservative, Baseline, and Optimistic technology cases. These values span the battery specific-energy range considered in the INDIGO battery technology assessment, with 800 Wh/kg representing the upper bound of the investigated range. This optimization campaign therefore allows the effect of increasing battery specific energy on the optimal aircraft and propulsion-system design to be assessed directly.

4.1.1. Mission Definition

The cruise altitude and Mach number are set to $h_{cr} = 8000 \text{ m}$ and $M_{cr} = 0.6$, respectively. To support a more detailed representation of airport-vicinity operations, both climb and descent are divided into segments below and above 900 m.

For the flight segments below 900 m, CRIDA provided radar-derived trajectories for Riga International Airport (RIX). These data define the altitude, speed, and flight-path-angle histories during the initial climb and final approach, allowing the low-altitude portions of the mission to reproduce representative airport-specific operations.

The portions of the trajectories above 900 m were generated numerically to obtain complete missions. During climb, the final point of the CRIDA trajectory is smoothly connected to the prescribed top-of-climb condition. During descent, the cruise condition is connected to the initial point of the CRIDA low-altitude descent trajectory. Spline-based interpolation is applied in both cases to ensure smooth variations in equivalent airspeed and flight-path angle.

The trajectory considered in the present optimization campaign is RIGA_TO_F597_L_F133, with a range of 1670.39 km and a payload of 18.657 t, as shown in Figure 23.



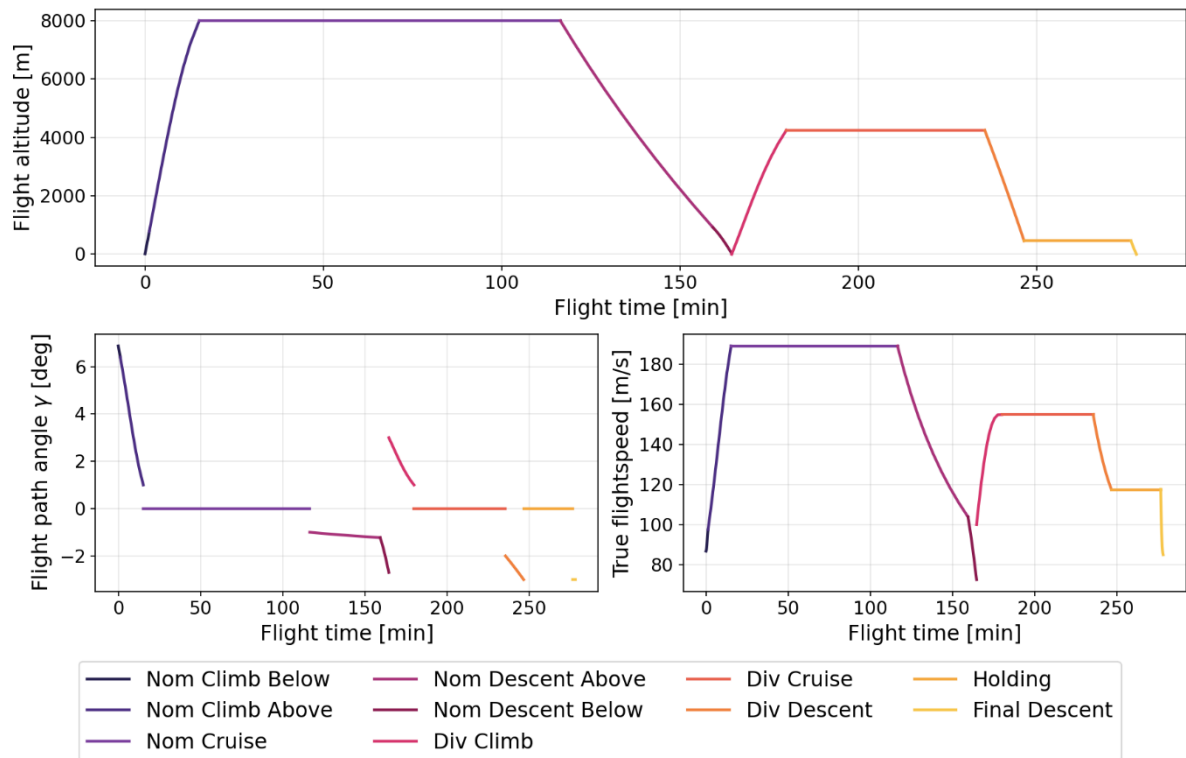


Figure 23 - RIGA_TO_F597_L_F133 altitude, flight path angle and true flight speed considered along the nominal (Nom) and diversion (Div) mission phases

4.1.2. Aircraft Concept

The results presented in this study use the fixed INDi2 airframe, whose main geometrical parameters are summarized in Table 15. Further details on the configuration are provided in Deliverables D3.2 and D5.2.

Component	Variable [Units]	Meaning	Value
Wing	AR	aspect ratio	21.62
	λ_{wing}	taper ratio	0.42
	t/c_{root} [%]	thickness to chord ratio at root	18.0
	t/c_{tip} [%]	thickness to chord ratio at tip	9.0
	S_W [m^2]	wing planform area	122.4
Strut	c_{strut} [m]	Chord	1.60

Table 15: INDIGO wing and strut geometrical parameters (INDi2)



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

4.1.3. Optimization Campaign

The optimization campaign was carried out using the MDO framework described in Deliverable D5.2. The following section presents the objective function and design variables considered in the optimization campaign, together with an analysis of the resulting optimal solutions. The optimization constraints are not repeated here, as they are identical to those already described in Deliverable D5.2. It is important to note that all results in this section considered a flyover EPNL constraint equal to 75.5 dB.

4.1.3.1. Objective Function

The objective function considered is the same as that adopted in the single-trajectory optimization campaign presented in Deliverable D5.2. The formulation consists of a weighted combination of the block fuel, denoted BF , and the fuel burned below 900 m, denoted by FB_{900} , during the nominal mission. This formulation therefore gives greater relevance to fuel consumption during low-altitude operations, with the aim of reducing aircraft emissions in the vicinity of airports. The objective function is defined as:

$$LAQ = 0.35 \frac{BF}{BF_{ref}} + 0.65 \frac{FB_{900}}{FB_{900,ref}},$$

where BF_{ref} and $FB_{900,ref}$ are reference values used to normalise the two contributions. The larger weight assigned to FB_{900} directs the optimisation towards reducing fuel consumption during the climb and descent portions below 900 m, while retaining sensitivity to the overall mission fuel requirement.

4.1.3.2. Design Variables

The design variables are summarized in table below. They are categorized based on their relevance to the powerplant components (excluding the propellers), the propellers themselves, or control parameters.

Variable	Units	Meaning	LB	UB
TOW	tons	takeoff weight	70.0	79.0
Powerplant				
$P_{TS,TOC}$	MW	turboshaft rating TOC	0.06	–
P_{gb}	MW	gearbox rating	0.5	–
$P_{IB,max}$	MW	IB peak design power	0.001	–
$P_{OB,max}$	MW	OB peak design power	0.001	–



Variable	Units	Meaning	LB	UB
W_{bat}	tons	battery weight	0.7	20.0
$\delta_{EPS,TO}$	–	EPS throttle at takeoff	0.1	0.9
Propellers				
$k_{RPM,LA}$	–	low-altitude multiplier	0.85	1.0
d_{IB}	m	diameter IB	1.0	5.0
d_{OB}	m	diameter OB	1.0	4.0
C_{TIB}	–	IB design thrust coefficient	0.2	0.5
C_{TOB}	–	OB design thrust coefficient	0.2	0.5
M_{tipIB}^*	–	sea-level tangential tip Mach	0.3	0.5
M_{tipOB}^*	–	sea-level tangential tip Mach	0.3	0.5
Each flight phase				
HF^*	–	local hybridization factor	-10.0	0.9
ψ	–	split factor	0.1	0.9
For each failure case				
$\delta_{EPS,FC}$	–	EPS throttle	0.1	0.9
$\delta_{TS,FC}$	–	turboshaft throttle	0.1	0.9
HF_{FC}^*	–	local hybridization factor	-10.0	0.9

Table 16: Design variables and their lower and upper bounds (LB and UB, respectively)

4.1.3.3. Results

Table 17 presents the optimal design and state variables for the three battery specific energy values considered, namely 400, 600, and 800 Wh/kg. The corresponding aircraft configurations are denoted as INDitech1, INDitech2, and INDitech3, respectively.

The reduction in both block fuel and fuel burned below 900 m with increasing battery specific energy leads to a progressive decrease in the weighted objective function. At the same time, the take-off weight remains at 79 t for all three configurations, while the optimal battery mass increases from 13.66 t at 400 Wh/kg to 16.27 t at 800 Wh/kg. As battery specific energy improves, the optimizer therefore allocates a larger fraction of the available aircraft mass to the battery, allowing a greater share of the mission energy to be supplied electrically and reducing the required fuel.

Regarding optimal design and state variables, as battery specific energy increases, the optimizer progressively shifts the propulsion system toward greater electrical utilization. This is reflected in the reduction of the required turboshaft top-of-climb rating, $P_{TS,TOC}$, which is consistent with the reduced dependence on turboshaft-generated power as the battery supplies a larger share of the mission energy.



The mission profiles further illustrate this redistribution of power. During cruise, the local hybridization factor (Figure 26) becomes progressively less negative as battery specific energy increases, indicating reduced generator operation of the IB electric machine. Consistently, the IB throttle (Figure 25) becomes less negative while the battery throttle increases, showing that a larger fraction of the electrical demand is supplied directly by the battery rather than through turboshaft-driven electrical generation.

This behaviour is captured more directly by the global hybridization factor (Figure 26), which increases with battery specific energy. The battery therefore supplies an increasingly large fraction of the total propulsion power as its specific energy improves. At the same time, the thrust-split parameter ψ (Figure 24) generally increases, particularly during climb and cruise, indicating a greater contribution of the OB propulsors to the total required thrust.

The IB and OB propeller efficiencies (Figure 24) change only slightly as the redistribution of thrust shifts the propellers to different operating points on their performance maps. However, these variations remain comparatively small. The dominant effect of increasing battery specific energy is therefore the redistribution of power from the turboshaft toward the battery and the associated increase in the contribution of the electrically driven OB propulsion system.

Variable	Units	INDitech1	INDitech2	INDitech3
		ED [Wh/kg]		
		400	600	800
TOW	tons	79.0	79.0	79.0
Powerplant				
$P_{TS,TOC}$	MW	3.81	3.06	2.45
P_{gb}	MW	2.73	2.48	2.87
$P_{IB,max}$	MW	6.74	5.41	5.87
$P_{OB,max}$	MW	10.27	11.00	10.69
W_{bat}	tons	13.66	14.99	16.27
$\delta_{EPS,TO}$	–	0.81	0.65	0.78
HF_{TO}^*	–	0.65	0.75	0.90
Propellers				
$k_{RPM,LA}$	–	0.87	0.88	0.88
d_{IB}	m	5.00	5.00	5.00
d_{OB}	m	4.00	4.00	4.00
C_{TIB}	–	0.41	0.37	0.42
C_{TOB}	–	0.34	0.35	0.33
M_{tipIB}^*	–	0.37	0.37	0.36
M_{tipOB}^*	–	0.40	0.40	0.40



Variable	Units	INDitech1	INDitech2	INDitech3
		ED [Wh/kg]		
		400	600	800
Failure				
$\delta_{EPS_{TO,FC1}}$	—	0.53	0.53	0.53
$HF_{TO_{FC1}}^*$	—	-0.14	-0.55	-0.55
$\delta_{TS_{TO,FC1}}$	—	0.4	0.4	0.40
$\delta_{EPS_{TO,FC2}}$	—	0.33	0.33	0.33
$HF_{TO_{FC2}}^*$	—	-0.14	-0.55	-0.55
Fuel indicators				
BF	tons	3.11	2.57	2.10
FB ₉₀₀	kg	80.98	64.83	51.74

Table 17: Optimal design variables and state variables (powerplant, propellers, failure variables, and fuel indicators)



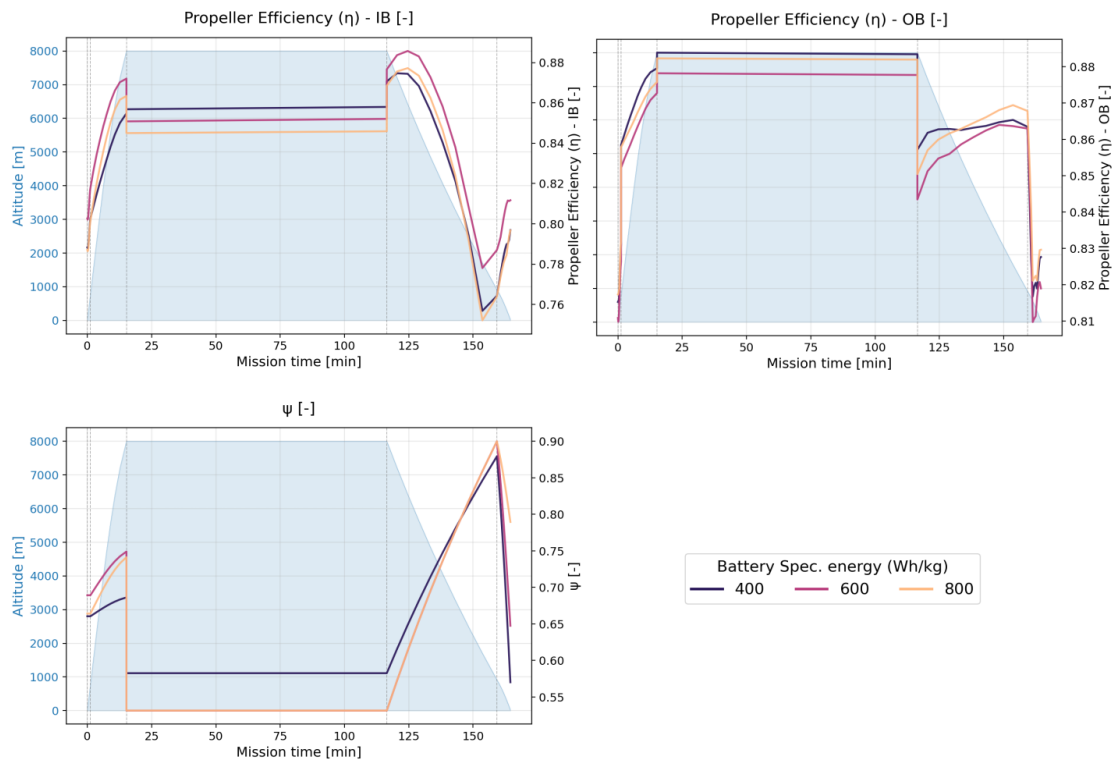


Figure 24 - Propellers efficiency, ψ , and overall powertrain efficiency along the mission

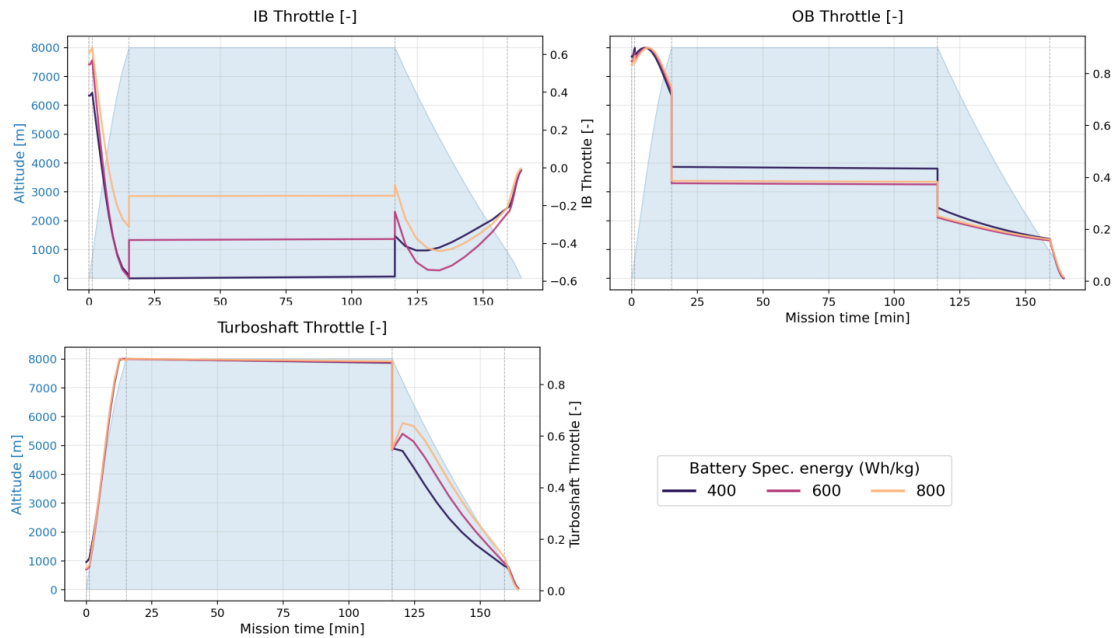


Figure 25 – Turboshift, Inboard (IB) and Outboard (OB) throttles

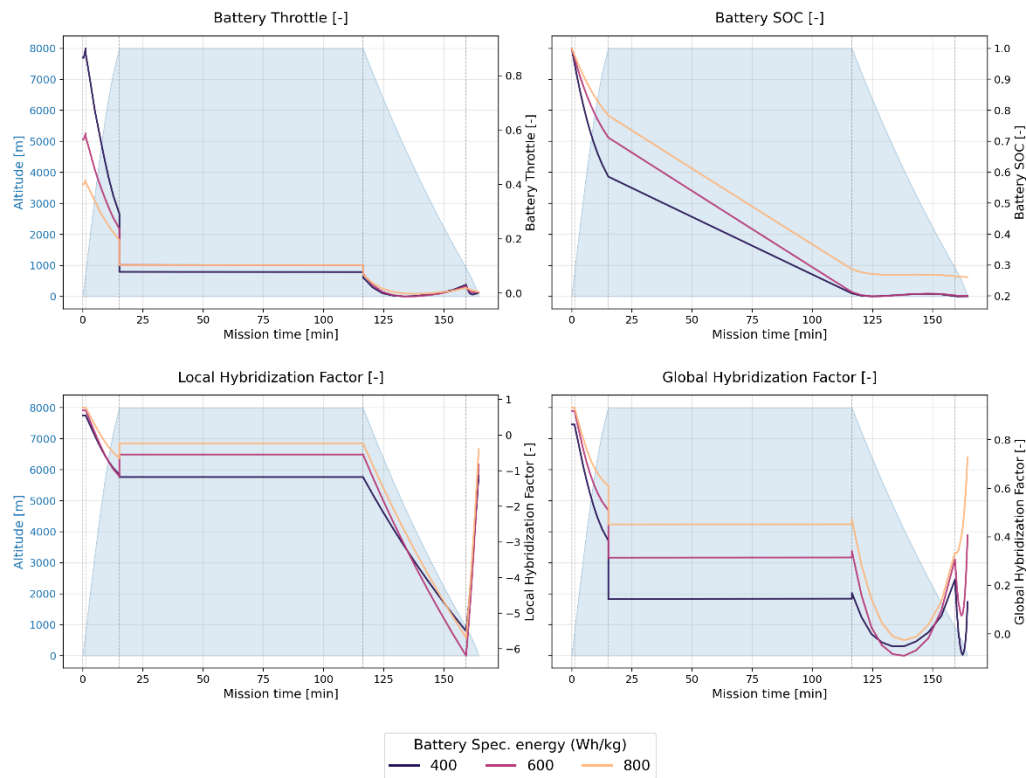


Figure 26 - Battery throttle, battery SOC, local and global hybridization factor along the mission

4.2. Exploration of the Use Case scenarios with respect to each configuration defined in the DoE

Building upon the aircraft-level Design of Experiments (DoE) presented in the previous section, the three configurations were propagated through the environmental assessment chain to investigate how the variations associated with battery specific energy translate into changes in Local Air Quality (LAQ) and noise performance in the airport vicinity. The analysis therefore focuses on the environmental response of the Conservative (400 Wh/kg), Baseline (600 Wh/kg) and Optimistic (800 Wh/kg) configurations, using the Baseline case as the reference for the sensitivity assessment.

For the LAQ analysis, pollutant concentrations were evaluated at a set of 13 virtual monitoring probes distributed within the simulation domain. The monitoring locations were selected with reference to urban areas and neighborhoods in the surroundings of Riga Airport, with the objective of reproducing, in a simplified manner, spatial sampling that would be provided by an air-quality monitoring network. The use of discrete monitoring locations was preferred to an indiscriminate average over the entire computational domain, since the latter could be strongly influenced by areas characterized by clean air or only residual pollutant concentrations, thereby diluting the differences associated with aircraft



plume. This approach consequently provides a more representative basis for comparing the environmental response of the three DoE configurations. All virtual monitoring probes were located at a height of 1.5 m above ground level. Their positions were subsequently verified with respect to the atmospheric modelling domain. Two initially considered locations were found to be close to or outside the relevant outflow boundary, where the resulting concentrations would not provide sufficiently robust information for the comparison. These locations were therefore excluded (probe number 5 and 14), resulting in the final set of 13 monitoring probes reported below.

ID	Lat	Long	x	y	z
1	56.89	24.05	2726.80	4964.60	1.50
2	56.90	23.97	2176.20	36.81	1.50
3	56.91	24.01	957.49	2362.00	1.50
4	56.91	24.08	324.31	6812.40	1.50
6	56.92	24.04	242.76	4062.70	1.50
7	56.88	23.99	4366.70	1702.10	1.50
8	56.86	24.08	6299.80	7372.60	1.50
9	56.89	24.08	3286.20	6701.70	1.50
10	56.92	23.98	236.98	410.74	1.50
11	56.85	24.04	7558.70	4681.10	1.50
12	56.90	24.07	2034.50	6195.30	1.50
13	56.92	24.02	56.07	2852.80	1.50
15	56.90	24.05	1500.50	5007.70	1.50

Table 18. Location and coordinates of the 13 virtual monitoring probes used for the LAQ sensitivity analysis

Specific meteorological and temporal conditions were also adopted to ensure that the sensitivity of the LAQ results to the investigated technological configurations could be adequately captured. In the nominal assessment, consistency between the meteorological conditions, aircraft trajectory, performance and environmental calculations is generally maintained. For this sensitivity exercise, however, a wind direction approximately perpendicular to the projected aircraft trajectory was considered. Under the initially available conditions, the wind direction was nearly parallel to the flight trajectory, causing a significant fraction of the pollutant plume to leave the computational domain before its dispersion and passage through the monitoring locations could be adequately characterized. The perpendicular wind configuration increases the residence time of the plume within the domain and consequently improves the ability of the virtual probes to capture differences among the three DoE configurations. It should therefore be interpreted as a specific sensitivity-analysis condition aimed at improving the observability of the environmental response, rather than as a representation of the prevailing meteorological conditions at Riga Airport.

Consistently, the temporal assessment window was extended to 2.5 h. Preliminary analysis showed that the initially considered one-hour interval was insufficient for the pollutant plume to reach the monitoring probes located farther downwind, particularly under the low



wind-speed conditions of the analyzed case. Extending the simulation window therefore allows the passage of the plume across the monitoring network to be represented more completely and reduces the risk of underestimating the response at the most distant locations.

For each DoE configuration and pollutant, the time-averaged concentration was first determined at each of the 13 virtual monitoring probes. The resulting set of probe-averaged concentrations was then used to characterize the spatial distribution of the LAQ response across the monitoring network. The reported mean, median, 95th percentile, maximum, standard deviation and coefficient of variation therefore describe the variability of the time-averaged concentrations among the selected monitoring locations, rather than the temporal variability at an individual probe.

The sensitivity of each environmental indicator relative to the Baseline configuration was additionally quantified through the Difference Percentage Ratio (DPR) and the corresponding elasticity indicators defined for the DoE. The DPR expresses the relative variation of the investigated metric with respect to the 600 Wh/kg Baseline configuration, while the elasticity quantifies the responsiveness of the environmental output to relative variations in the corresponding DoE input parameter. The same overall comparison framework was applied to the noise results, allowing the environmental implications of the three configurations to be assessed consistently across LAQ and acoustic performance.

The subsequent tables present the resulting LAQ concentration statistics for CO, NO_x, PM and HC, followed by the corresponding noise sensitivity results. The LAQ results show that the environmental response to battery specific energy is pollutant-dependent. This indicates that the relationship between battery technology improvement and airport-vicinity LAQ is influenced not only by the total amount of fuel consumed, but also by the resulting propulsion-system operating conditions and by the spatial dispersion of the emitted pollutants.

The aircraft-level DoE indeed shows that increasing battery specific energy modifies the balance between thermal and electrical propulsion and changes several powerplant operating parameters, while TOW remains constant at 79 t.



Case	Conservative	Baseline	Optimistic
Metric	400 Wh/kg	600 Wh/kg	800 Wh/kg
Mean [$\mu\text{g}/\text{m}^3$]	0.00217	0.00168	0.00134
Median [$\mu\text{g}/\text{m}^3$]	3.89×10^{-5}	3.00×10^{-5}	2.41×10^{-5}
Percentile 95 [$\mu\text{g}/\text{m}^3$]	0.0129	0.00994	0.00797
Maximum [$\mu\text{g}/\text{m}^3$]	0.0194	0.0150	0.0120
Standard deviation [$\mu\text{g}/\text{m}^3$]	0.00491	0.00380	0.00305
Coefficient of variation [%]	2.68	2.68	2.68
DPR vs. baseline[%]	29.10	0.00 (ref.)	-19.82
Elasticity vs. battery density	-0.872	0.00 (ref)	-0.595

Table 19: CO concentration statistics and sensitivity indicators

Case	Conservative	Baseline	Optimistic
Metric	400 Wh/kg	600 Wh/kg	800 Wh/kg
Mean [$\mu\text{g}/\text{m}^3$]	0.0359	0.0249	0.02
Median [$\mu\text{g}/\text{m}^3$]	0.000641	0.000447	0.000359
Percentile 95 [$\mu\text{g}/\text{m}^3$]	0.213	0.148	0.119
Maximum [$\mu\text{g}/\text{m}^3$]	0.323	0.224	0.180
Standard deviation [$\mu\text{g}/\text{m}^3$]	0.0817	0.0565	0.0475
Coefficient of variation [%]	2.67	2.67	2.67
DPR vs. baseline[%]	44.70	0.00 (ref.)	-19.60
Elasticity vs. battery density	-1.34	0.00 (ref.)	-0.589

Table 20: NOx concentration statistics and sensitivity indicators



Case	Conservative	Baseline	Optimistic
Metric	400 Wh/kg	600 Wh/kg	800 Wh/kg
Mean [$\mu\text{g}/\text{m}^3$]	0.000161	0.000121	9.68×10^{-5}
Median [$\mu\text{g}/\text{m}^3$]	2.86×10^{-6}	2.17×10^{-6}	1.74×10^{-6}
Percentile 95 [$\mu\text{g}/\text{m}^3$]	0.000957	0.000716	0.000574
Maximum [$\mu\text{g}/\text{m}^3$]	0.00145	0.00108	0.000867
Standard deviation [$\mu\text{g}/\text{m}^3$]	0.000366	0.000274	0.000219
Coefficient of variation [%]	2.79	2.79	2.79
DPR vs. baseline[%]	33.60	0.00 (ref.)	-19.90
Elasticity vs. battery density	-1.01	0.00 (ref.)	-0.596

Table 21: PM concentration statistics and sensitivity indicators

Case	Conservative	Baseline	Optimistic
Metric	400 Wh/kg	600 Wh/kg	800 Wh/kg
Mean [$\mu\text{g}/\text{m}^3$]	0.000189	0.000140	0.000112
Median [$\mu\text{g}/\text{m}^3$]	3.38×10^{-6}	2.51×10^{-6}	2.01×10^{-6}
Percentile 95 [$\mu\text{g}/\text{m}^3$]	0.00112	0.000829	0.000666
Maximum [$\mu\text{g}/\text{m}^3$]	0.00170	0.00125	0.00101
Standard deviation [$\mu\text{g}/\text{m}^3$]	0.000429	0.000317	0.000254
Coefficient of variation [%]	2.79	2.79	2.79
DPR vs. baseline[%]	35.30	0.00 (ref.)	-19.80
Elasticity vs. battery density	-1.06	0.00 (ref.)	-0.594

Table 22: HC concentration statistics and sensitivity indicators

The LAQ sensitivity analysis shows a consistent improvement in local air-quality performance as battery specific energy increases. Across the pollutants considered, the transition from the Conservative to the Baseline and subsequently to the Optimistic configuration is associated with progressively lower pollutant concentrations. The environmental response



therefore follows the same overall direction as the aircraft-level energetic improvement identified by the DoE, although the magnitude of the response differs among pollutants.

For CO, NO_x, PM and HC, the reduction is observed across the concentration distributions rather than being limited to the mean values. Median concentrations, upper-percentile values and maximum concentrations generally decrease towards the Optimistic configuration, indicating that the improvement affects both the overall concentration field and the monitoring locations experiencing the highest pollutant levels. The consistently negative battery-density elasticities further indicate an inverse relationship between battery specific energy and the resulting local pollutant concentrations.

The sensitivity is nevertheless pollutant dependent. The magnitude of the response differs among CO, NO_x, PM and HC, showing that improvements in battery technology do not propagate identically through the different emission pathways. The results should therefore not be interpreted as a uniform scaling of all pollutants, but rather as a common decreasing tendency whose magnitude depends on the pollutant considered and on the associated propulsion and emission mechanisms.

A further relevant feature is the pronounced spatial heterogeneity across the virtual monitoring network. The differences between median and mean concentrations, together with the upper-percentile and maximum values, indicate that the pollutant field is strongly non-uniform across the selected monitoring locations. Higher concentrations are concentrated at a subset of probes more directly affected by plume transport, whereas other monitoring locations experience substantially lower concentrations. This supports the use of spatially distributed virtual monitoring probes rather than a whole-domain average, which could dilute the plume signal through the inclusion of extensive areas characterized by clean or residual concentrations.

Despite the reduction in absolute concentrations, the coefficient of variation remains essentially unchanged across the three configurations for each pollutant. This suggests that increasing battery specific energy primarily reduces the magnitude of the concentration field without substantially modifying its relative spatial distribution. In other words, the locations most strongly affected by the plume remain broadly similar, but the concentration levels experienced across the monitoring network decrease as the technological configuration improves.

Overall, the LAQ results indicate that increasing battery specific energy provides a systematic local air-quality benefit under the conditions considered in the sensitivity analysis. The Conservative configuration consistently represents the highest-impact condition, while the Optimistic configuration produces the lowest concentration levels. The Baseline case lies between these two technological extremes. The sensitivity analysis therefore establishes a coherent relationship between the technological progression represented by the DoE and the resulting LAQ performance, while also showing that the strength of this relationship remains pollutant specific.



Case	Conservative	Baseline	Optimistic
Metric	400 Wh/kg	600 Wh/kg	800 Wh/kg
Mean [dB]	156.69	157.12	156.82
Median [dB]	155.71	155.84	155.77
Percentile95 [dB]	158.87	159.57	159.12
Maximum [dB]	159.64	159.96	159.61
Standard deviation	1.91	2.26	2.12
Coefficient of variation [%]	0.01	0.01	0.01
DPR vs. baseline [%]	-0.28	0.00 (ref.)	-0.19
Elasticity vs. battery density	0.01	0.00 (ref.)	-0.01

Table 23: Noise (SPoL) sensitivity to battery specific energy

The noise sensitivity analysis indicates that battery specific energy has a relatively limited influence on the acoustic response of the investigated aircraft configuration. Unlike the clear improvement observed in the aircraft-level energy indicators, the noise results do not exhibit a monotonic trend with increasing battery specific energy. Both the Conservative and Optimistic configurations show only limited differences relative to the Baseline case, suggesting that battery technology improvement alone does not produce a proportional reduction in the considered noise indicator.

This behavior can be interpreted in relation to the aircraft-level optimization results. Increasing battery specific energy significantly modifies the distribution of power between the thermal and electrical branches of the propulsion system, but the optimized parameters that are particularly relevant to low-altitude propeller operation remain comparatively stable across the three configurations. In particular, the low-altitude RPM multiplier varies only marginally, while the optimized inboard and outboard propeller diameters remain unchanged. Consequently, the substantial changes in energy source and hybridization identified by the DoE do not translate into equally substantial modifications of the acoustic response.

The results therefore suggest that, within the technological range investigated, noise performance is comparatively insensitive to battery specific energy itself. The small differences among the three configurations are more consistent with changes in the optimized propulsion-system operating point than with a direct relationship between increasing battery performance and decreasing noise.

This distinction is relevant for the interpretation of the sensitivity analysis. Higher battery specific energy provides clear aircraft-level benefits in terms of fuel consumption and electrical utilization, but these benefits should not be assumed to generate an equivalent acoustic improvement. The results instead indicate that further reductions in airport-vicinity



noise would likely depend on changes to parameters more directly governing acoustic generation, such as propeller operating conditions and other noise-oriented design variables, rather than on battery specific energy alone.

As a general conclusion of this analysis, the LAQ results show a consistent reduction in pollutant concentrations as battery specific energy increases. This trend is observed for CO, NO_x, PM and HC and across the different statistical indicators, indicating that the improvement is not restricted to average concentration but extends to the overall concentration distributions across the monitoring network. The negative battery-density elasticities further support this inverse relationship. Nevertheless, the magnitude of the response remains pollutant-dependent, with NO_x showing the strongest sensitivity to technological variation. The noise response is comparatively less sensitive to battery specific energy. Although differences are observed among the three configurations, they are relatively limited and do not exhibit the same clear progression found for the LAQ indicators. This suggests that the technological changes associated with improved battery performance have a more direct influence on the local emission-related indicators than on the acoustic response under the conditions considered.

Overall, the sensitivity analysis indicates that increasing battery specific energy provides benefits at both aircraft and local air-quality levels, while its influence on noise remains more limited. However, the environmental response should not be inferred solely from aircraft-level indicators such as fuel consumption or degree of hybridization. The magnitude of the resulting benefit depends on how the technological changes propagate through the emission, dispersion and acoustic mechanisms represented in the assessment chain.



5. LAQ and Noise results assessment

5.1. Applicable metrics and indicators

INDIGO indicators		
Area	Type	Indicator
Noise	SESAR-NOI	LDEN (noise perception): above 55dB (regarding regulation)
	SESAR-NOI4	Population exposed to an exceeded threshold (using official population values)
LAQ (emissions)	Gaseous emission (carbon)	CO
	Gaseous emission (HC)	VOC: MHC and non-MHC
	Gaseous emission (env)	NOx
	Particulate Matter	PM2.5/10: volatile and non volatile
	Particulate Matter	Black Carbon (BC)

Table 24: INDIGO environmental indicators

All the proposed metrics can be measured with respect its reference value for each UC and presented following their stablished regulations (defined in D1.1 [3]). Depending on the pollutant to be analysed, different metrics are established, tailored to the specific characteristics of each pollutant to be presented in reports, on the assumption that the receptors act as air quality stations:

Pollutant	Metric
CO	Maximum 8-hour moving average in a day at receptor level
HC	Daily average at receptor level
NOx	Maximum hourly averaged value at receptor level
NOx	Daily average at receptor level
PM	Daily average at receptor level
BC	Daily average at receptor level

Table 25: Metrics calculated by pollutant



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

5.2. Results

For each airport, the average variations and global results in terms of Local Air Quality and Noise are presented for the Solution Scenarios (SOL 40%), compared with Reference, in order to assess the benefit for each pollutant (LAQ) and reductions in SPoL (Noise). Then, results are consolidated to show the maximum potential of INDIGO aircraft per pollutant and noise indicator.

5.2.1. Riga airport

5.2.1.1. LAQ

LAQ results will be shown for each pollutant: figures with the spatial distribution of the pollutant concentration for both REF and SOL40 scenarios, followed by tables containing the benefit in LAQ achieved in all solution scenarios.

CO

The comparison of the spatial distributions shows a clear improvement in CO concentrations after applying the INDIGO solution. In the reference scenario shown in Figure 27, a wide area in the East of the airport is affected with concentration top values reaching $7 \mu\text{g}/\text{m}^3$. After the application of INDIGO, it can be appreciated in Figure 28 that the extension with remarkable CO concentrations is reduced, and most of the receptors get values under $7 \mu\text{g}/\text{m}^3$.

The analysis of the CO 8-hour running average confirms the improvement observed in the spatial distributions. All four solution scenarios produce reductions of the CO levels relative to the reference scenario in a progression, starting with the 12.75% reduction for SOL10 scenario, reaching the top improvement with the decrease of the 49.34% in SOL40 scenario.

Overall, the results demonstrate that the application of INDIGO can substantially decrease both the magnitude and spatial dispersion of CO concentrations around the airport. Among the scenarios assessed, SOL40 delivers the strongest improvement in the CO 8-hour running average.



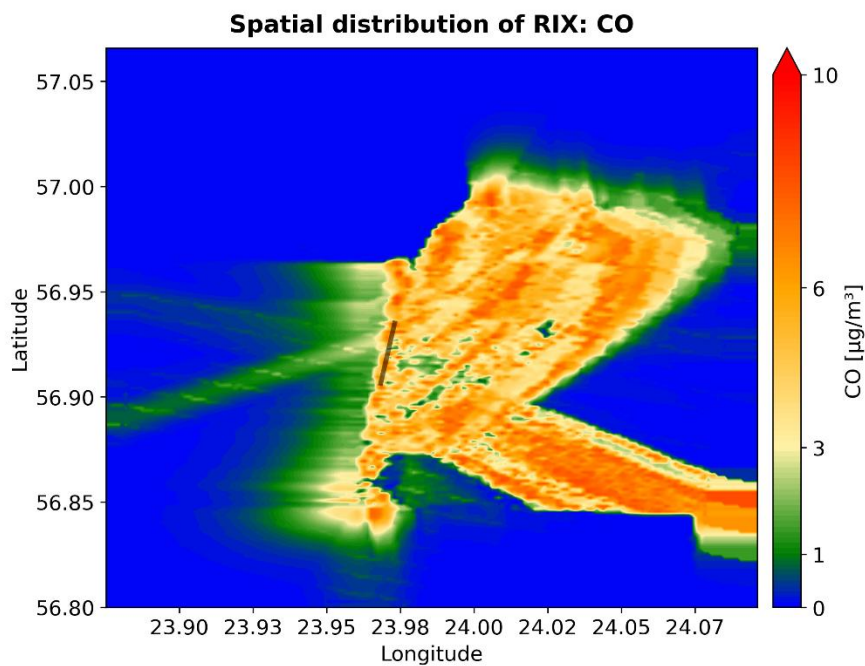


Figure 27: Spatial distribution of CO in RIX airport Reference scenario

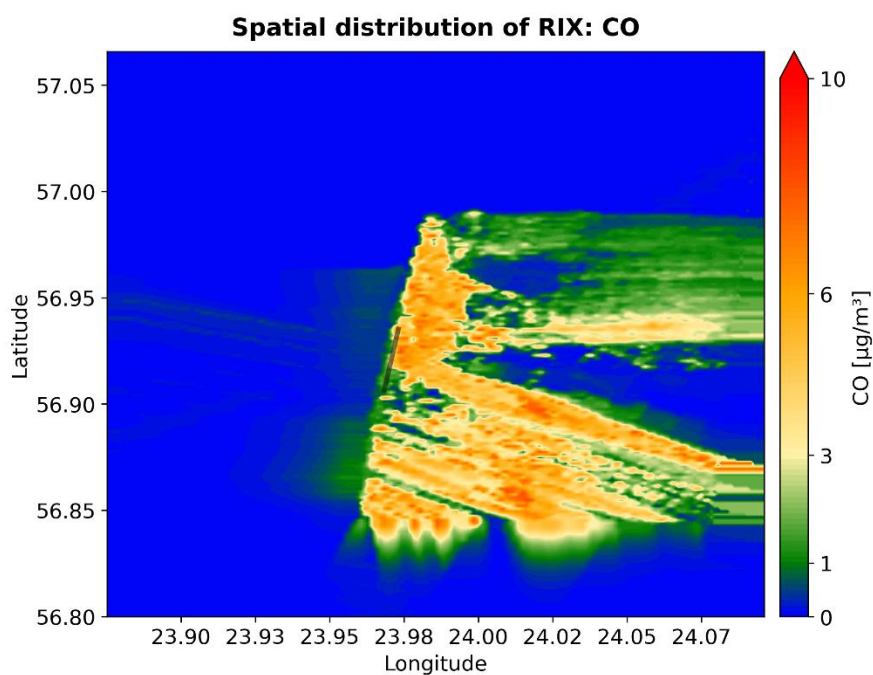


Figure 28: Spatial distribution of CO in RIX airport SOL40 scenario



Scenario	Average reduction (%)
SOL10	12.75
SOL20	23.20
SOL30	46.10
SOL40	49.34

Table 26: CO 8-hour running average reductions relative to RIX Reference scenario

HC

The comparison of the spatial distributions shows a clear improvement in HC concentrations after applying the INDIGO solution. In the reference scenario, it is shown in Figure 29 pollution area is much wider than in SOL40, reaching at some locations of around $5 \mu\text{g}/\text{m}^3$. After the application of INDIGO, in Figure 30 fewer HC concentrations are observed and never reaching values over $4 \mu\text{g}/\text{m}^3$.

The quantitative results support the improvement observed in the spatial maps. All four solution scenarios reduce the mean HC concentration relative to the reference scenario. The reduction increases progressively across the assessed scenarios, from 7.91% in SOL10 to 50.28% in SOL40. It is worth mentioning that, even though improvements are progressive, this evolution is not gradual. SOL30 scenario increases in comparison with the previous (SOL20) faster than others. This happens because of the difficulty that supposes introducing INDIGO aircraft in traffic of this airport, following the replaceability and flyability rules (See Assumption 3 of Section 1).

Overall, the INDIGO solutions substantially reduce both the intensity and geographical spread of HC concentrations around the airport.

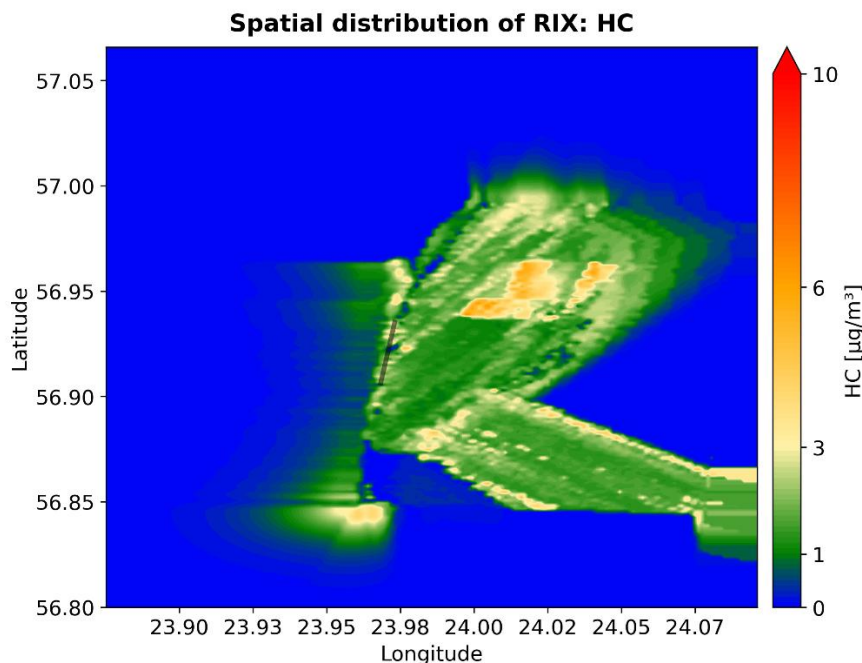


Figure 29: Spatial distribution of HC in RIX airport Reference scenario



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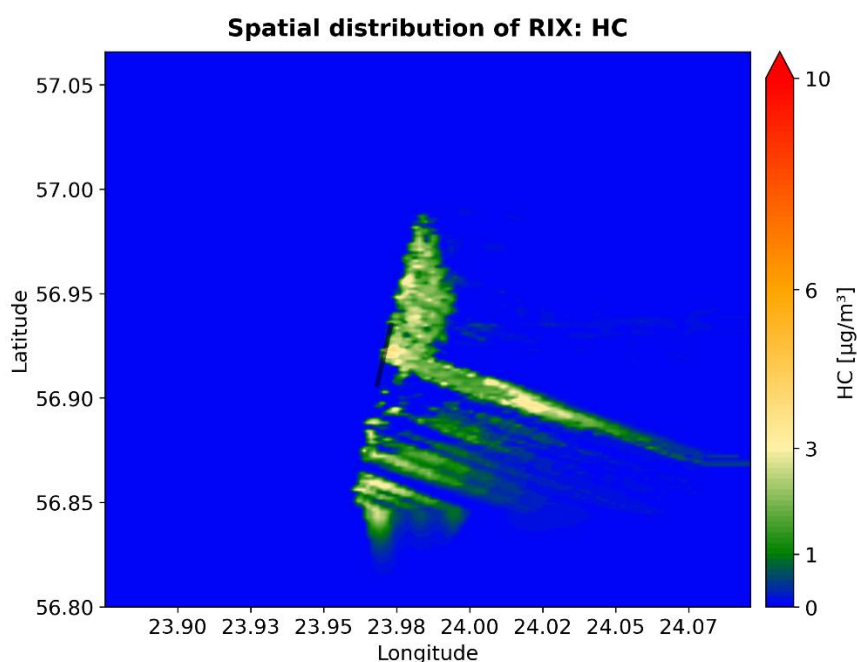


Figure 30: Spatial distribution of HC in RIX airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	7.91
SOL20	9.26
SOL30	44.30
SOL40	50.28

Table 27: Average reduction of HC daily mean concentration relative to RIX Reference scenario

NO_x

The spatial distribution of the daily mean concentration shows a substantial improvement in SOL40 compared with the reference scenario. In reference, Figure 31 shows that concentrations are extended over the East of the airport, with several receptors with values of 5 µg/m³ and 6 µg/m³. Under SOL40, according to Figure 32 both the magnitude and geographical extent of these concentrations decrease considerably. Number of peak concentrations is reduced, and their values do not exceed 5 µg/m³.

The quantitative results in Table 28 confirm reductions in the daily mean NO_x concentration for all four solution scenarios. The mean reduction increases progressively from 12.39% in SOL10 to 20.15% in SOL40, which therefore provides the greatest improvement.



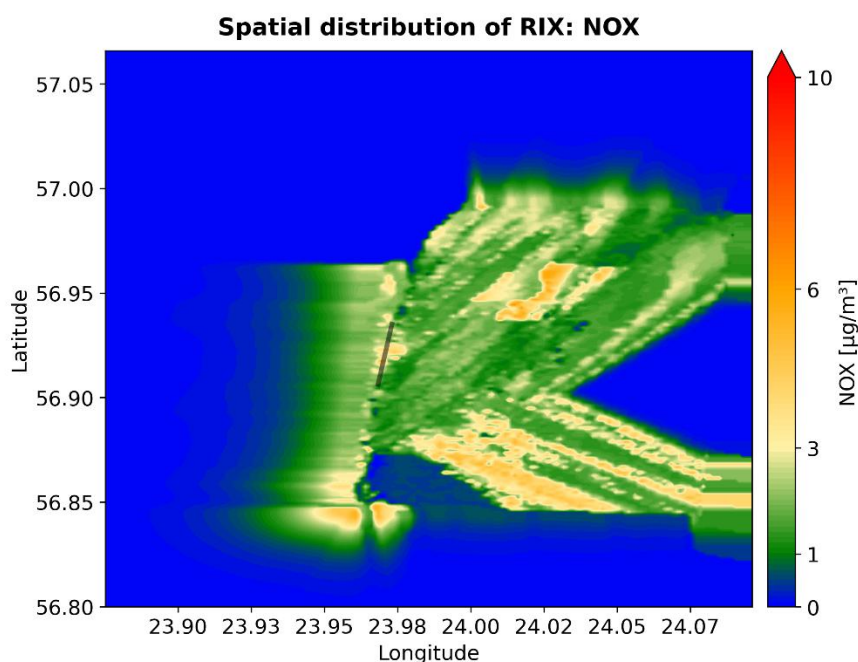


Figure 31: Spatial distribution of NOX daily mean concentration in RIX airport Reference scenario

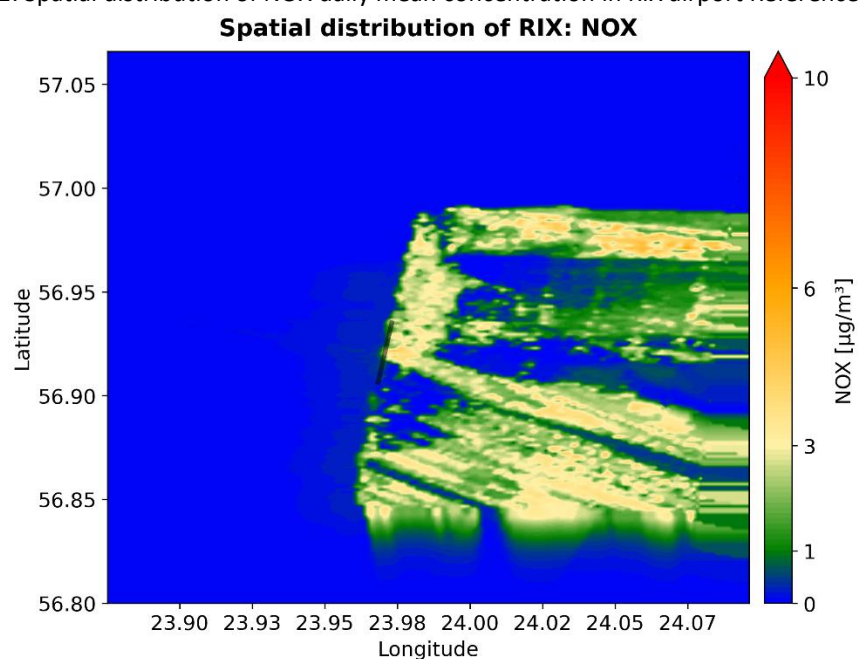


Figure 32: Spatial distribution of NOX daily mean concentration in RIX airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	12.39
SOL20	13.77
SOL30	18.93
SOL40	20.15

Table 28: Average reduction of NOX daily mean concentration relative to RIX Reference scenario



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Regarding the metric NOX maximum hourly average concentration at receptor, spatial distribution is quite similar in SOL40, seen in Figure 34 compared with the reference scenario, Figure 33 except for a significative reduction of affection at the western part. In terms of maximums, in both scenarios reach between $8 \mu\text{g}/\text{m}^3$ and $10 \mu\text{g}/\text{m}^3$.

The quantitative results in Table 29 confirm low and progressive reductions in this metric for all four solution scenarios, from 8.34% in SOL10 to 16.08% in SOL40, which therefore provides the greatest improvement.

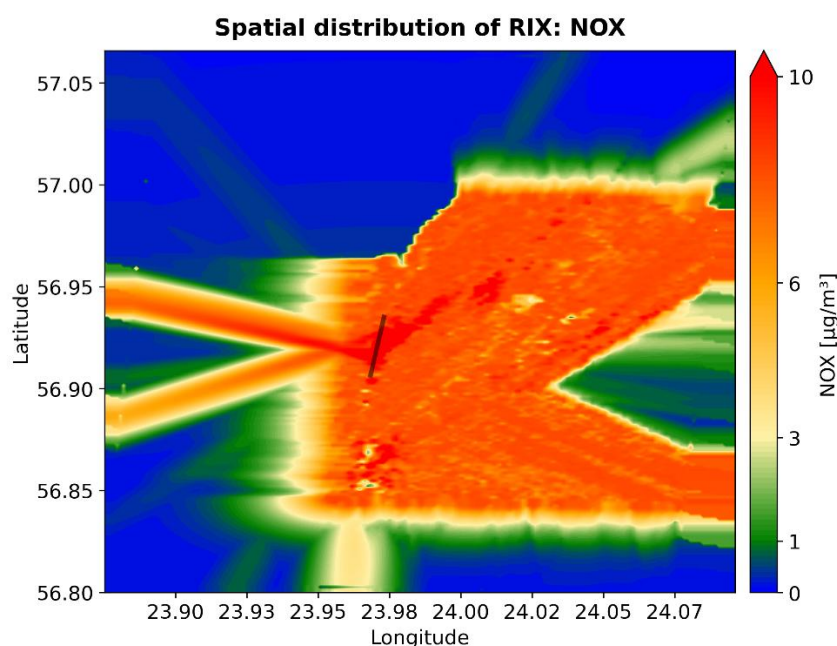


Figure 33: Spatial distribution of NOX maximum hourly average concentration at receptor in RIX airport Reference scenario



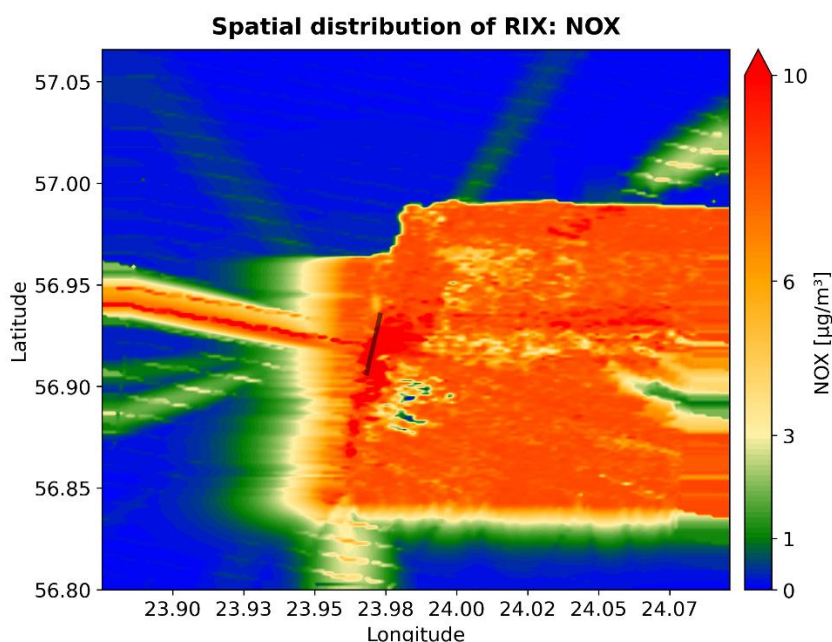


Figure 34: Spatial distribution of NOX maximum hourly average concentration at receptor in RIX airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	8.34
SOL20	9.09
SOL30	14.86
SOL40	16.08

Table 29: Average reduction of NOX maximum hourly average concentration at receptor relative to RIX reference scenario

PM

The comparison of the spatial distributions shows a substantial decrease in PM concentrations after applying INDIGO. In the reference scenario, the most elevated concentrations are observed in Figure 35 over the eastern area of the airport, reaching values of $3 \mu\text{g}/\text{m}^3$.

Under SOL40, spatial extent of PM concentrations decreases considerably as observed in Figure 36, while intensity maintains with peaks of $3 \mu\text{g}/\text{m}^3$, being more located in areas closer to the runway.

The quantitative results in Table 30 confirm the improvement observed in the spatial distributions. A low progression in concentration reduction starts with SOL10 decrease of PM concentration of 4.71% and ends with a 19.61% in SOL4, which achieves the greatest reduction.



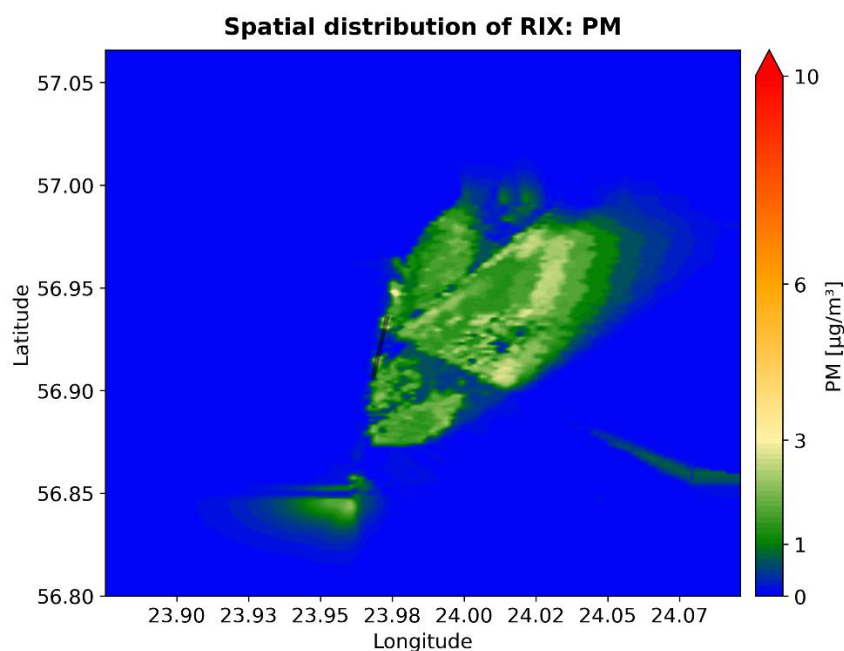


Figure 35: Spatial distribution of PM in RIX airport Reference scenario for the metric daily mean concentration

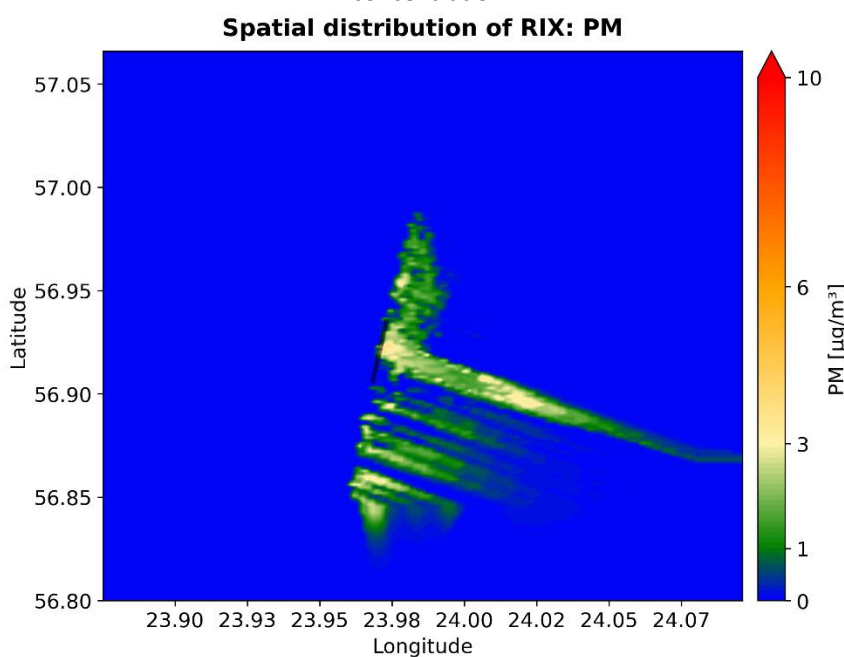


Figure 36: Spatial distribution of PM in RIX airport SOL40 scenario for the metric daily mean concentration

Scenario	Average reduction (%)
SOL10	4.71
SOL20	8.35
SOL30	17.68
SOL40	19.61

Table 30: Average reduction of PM daily average concentration relative to RIX Reference scenario



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

BC

BC concentrations were assessed using the daily mean concentration and are expressed in ng/m^3 . BC is characterised as a LAQ pollutant, but it also contributes to global warming and has a similar behaviour as GHGs. Its emissions are expressed as mass fractions of PM emissions. Its atmospheric concentrations are therefore generally much lower than total PM concentrations. Using nanograms per cubic meter provides a more practical and readable numerical scale for reporting these comparatively small values.

The spatial distributions show that BC concentrations are strongly concentrated around the airport infrastructure in all scenarios. In the reference scenario, pronounced peaks occur near the main airport emission sources, as shown in Figure 37 with concentration values of $10 \text{ ng}/\text{m}^3$. Even though under SOL40 maximums reach similar values, the amount of them decreases as their geographical extent is reduced, seen in Figure 38.

The quantitative results in

Table 31 confirm reductions in average BC concentrations for all four solution scenarios. The average reduction increases progressively from 4.71% in SOL10 to 28.74% in SOL40, which therefore provides the greatest improvement.

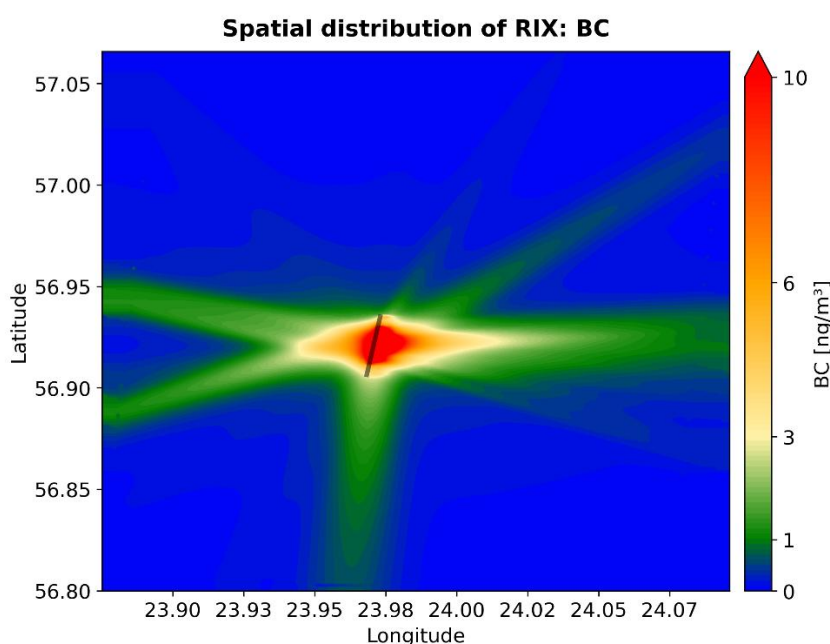


Figure 37: Spatial distribution of BC in RIX airport Reference scenario



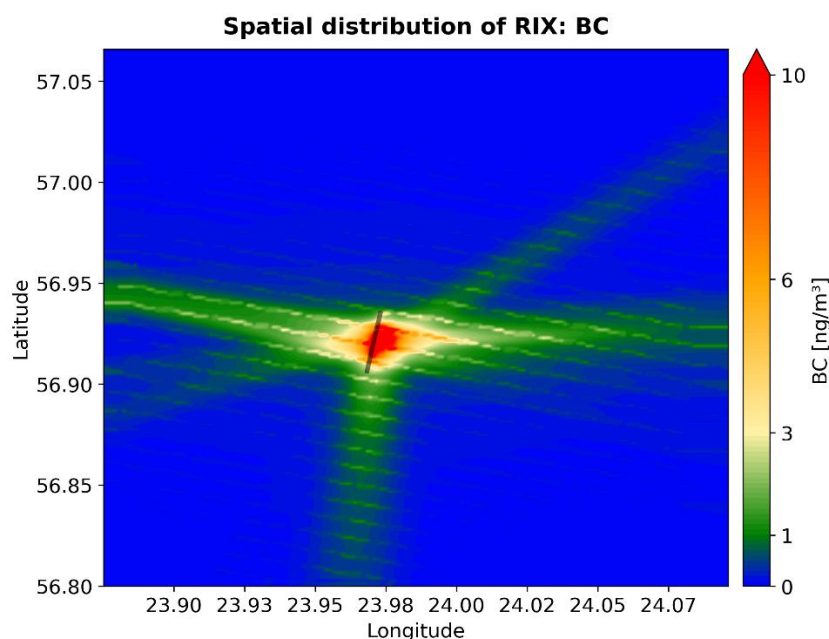


Figure 38: Spatial distribution of BC in RIX airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	4.71
SOL20	8.36
SOL30	17.70
SOL40	28.74

Table 31: Average reduction of BC daily mean concentration relative to RIX reference scenario

Conclusion

According to the summary presented in Table 32, the SOL40 scenario produces reductions for all pollutants considered, with mean improvements ranging from 19% to almost 50%. The greatest reduction is observed for CO and HC, at 49.34% and 50.28%, respectively, and both followed by BC concentration reduction of 28.74%. PM and NO_x show similar improvements, with reductions around between 16% and 20%.

Overall, these results indicate that SOL40 has a consistently positive effect on local air quality, reducing the concentrations of every pollutant assessed. The improvement is particularly pronounced for HC and CO, while the reductions in BC, PM and NO_x are more moderate but remain relevant.



Pollutant	Metric	Average Reduction under SOL40 (%)
CO	max. 8h	49.34
HC	daily mean	50.28
NOX	daily mean	20.15
NOX	Max. hourly	16.08
PM	daily mean	19.61
BC	daily mean	28.74

Table 32: Result summary SOL40 relative to RIX reference scenario

5.2.1.2. Noise

In order to ensure consistency between the metrics, the threshold selected for the population exposed is 55 dB(A).

The LDEN noise footprints is generated by following the methodology described in section 3.5.2 and represented using GIS tools and nearest neighbor algorithm:



Figure 39. RIGA LDEN footprint

The results for Reference and Solution 40% scenarios are presented below:



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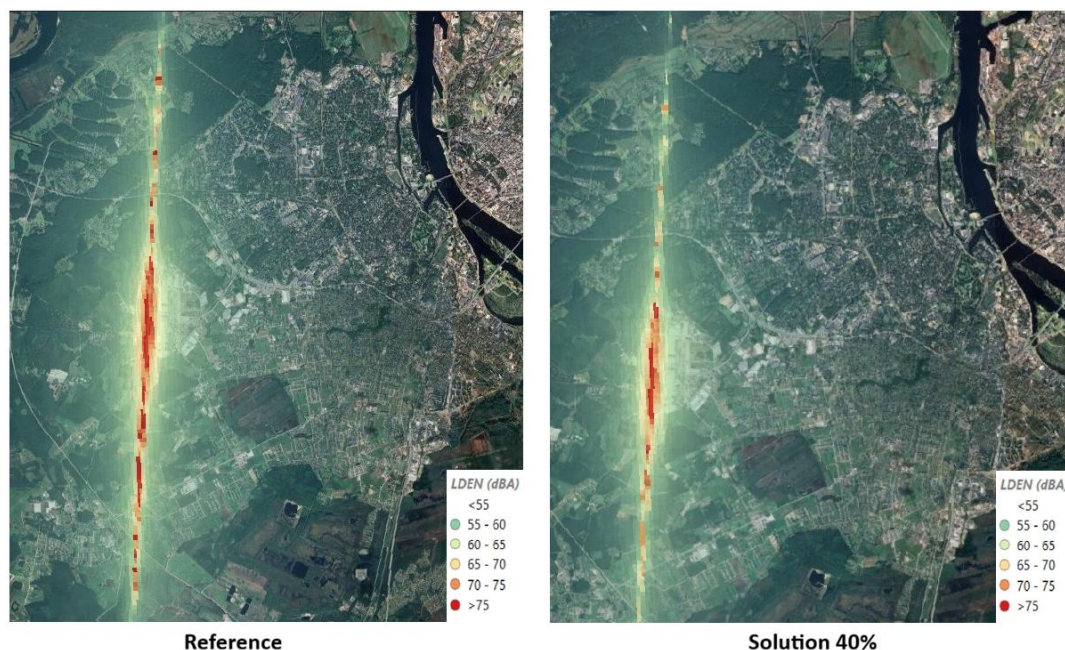


Figure 40. Comparison of LDEN results for Reference and Solution scenarios at RIX

As for the population exposed to more than 55 dB(A), the following table shows the results for each of the scenarios:

Scenario	Population exposed to more than 55 dBA (inhabitants)	Average reduction (%)
Reference	2340	-
Solution 10%	1820	22
Solution 20%	1445	38
Solution 30%	775	66
Solution 40%	510	78

Table 33. Population exposed in each scenario at RIX

Additionally, a spatial distribution of the population exposed is represented in the figure below:





Figure 41. Comparison of population exposed before (left) and after (right) INDIGO introduction at RIX

The results show a clear and progressive reduction in the population exposed to high levels of aircraft noise as the proposed solution increases. For the reference scenario, a total of 2340 inhabitants are exposed to noise levels above 55 dBA. This population decreases progressively to 510 inhabitants under Solution 40% scenario, corresponding to an overall reduction of 78%.

The intermediate solutions also show a substantial reduction, with the population exposed above 55 dBA decreasing by 22%, 38% and 66% for 10%, 20% and 30% of replacement, respectively. The improvement observed from Solution 20% onwards demonstrates a significant effect on the areas experiencing the highest noise levels.

The spatial distribution shown in the LDEN map (noise footprint) is consistent with these results. In the Reference scenario, the highest noise levels are concentrated along the airport runway and flight path, with a continuous area of higher noise extending through the surrounding territory. In Solution 40% scenario, the extent of these higher noise levels is visibly reduced, particularly around the most affected sections of the flight path. The areas exceeding the highest noise categories become more limited and fragmented, indicating a substantial reduction in the population exposed to the most intense levels of aircraft noise.

The maps representing the affected population provide further evidence of this improvement. In the reference scenario, several locations show relatively high numbers of inhabitants affected. Bringing INDIGO Solution scenarios, these values are substantially



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reduced, with most locations showing much lower values and the areas of concentrated population impact becoming considerably less extensive. This spatial reduction is consistent with the 78% decrease in the total population exposed to above 55 dBA.

The results therefore indicate that the replacement of 40% of the traffic by INDIGO is particularly effective in reducing high-level noise exposure, which is important because these areas represent the population subject to the most significant acoustic impact. The reduction is not only reflected in the aggregated population figures but is also clearly visible in the geographical distribution of the noise contours and affected population.

In conclusion, the implementation of INDIGO can be expected to provide significant benefits to the population living around the airport, by reducing exposure to the highest aircraft noise levels and decreasing the number of inhabitants affected by these levels. This reduction in noise exposure can contribute to improved living conditions and quality of life, through a more favorable acoustic environment.

5.2.2. Dortmund airport

5.2.2.1. LAQ

LAQ results will be shown for each pollutant: figures with the spatial distribution of the pollutant concentration for both REF and SOL40 scenarios, followed by tables containing the benefit in LAQ achieved in all solution scenarios.

CO

The comparison of the spatial distributions shows a clear improvement in CO concentrations after applying the INDIGO solution. In the reference scenario, it is observed in Figure 42 how elevated concentrations cover a relatively extensive area, with values very close to $7 \mu\text{g}/\text{m}^3$. After the application of INDIGO, Figure 43 shows that the areas with moderate or high CO concentrations become smaller and more localized, most of them under $6 \mu\text{g}/\text{m}^3$, and very few of them reaching $7 \mu\text{g}/\text{m}^3$ as the highest value.

The analysis of the CO 8-hour running average in Table 34 confirms the improvement observed in the spatial distributions. All four solution scenarios produce reductions of the CO levels relative to the reference scenario in progression, starting with the 27.70% reduction for SOL10 scenario, reaching the top improvement with the decrease of the 52.69% in SOL40 scenario.

Overall, the results demonstrate that the application of INDIGO can substantially decrease both the magnitude and spatial extent of CO concentrations around the airport. Among the scenarios assessed, SOL40 delivers the strongest improvement in the CO 8-hour running average.



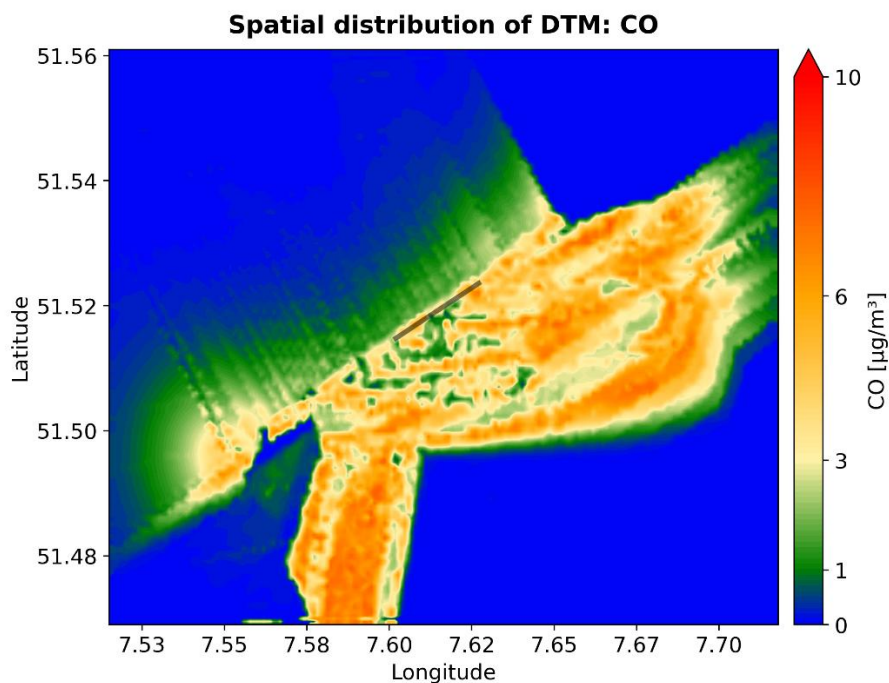


Figure 42: Spatial distribution of CO in DTM airport Reference scenario

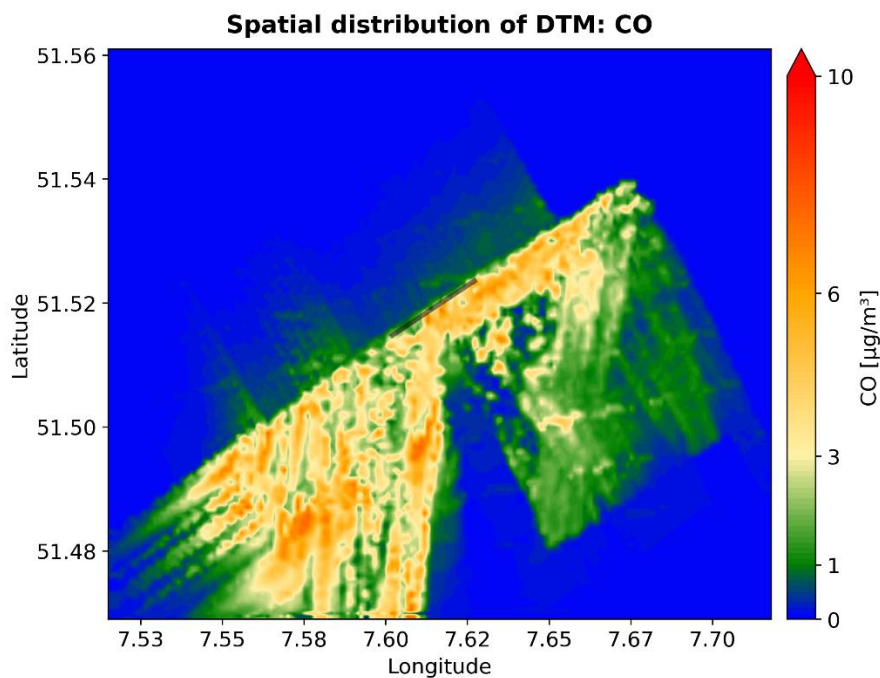


Figure 43: Spatial distribution of CO in DTM airport SOL40 scenario



Scenario	Average reduction (%)
SOL10	27.20
SOL20	48.27
SOL30	50.93
SOL40	52.69

Table 34: CO 8-hour running average reductions relative to DTM Reference scenario

HC

The comparison of the spatial distributions shows a clear improvement in HC concentrations after applying the INDIGO solution. In the reference scenario, Figure 44 shows that pollution area is wide, reaching some peaks of around $5 \mu\text{g}/\text{m}^3$. After the application of INDIGO, in Figure 45 the area with significative values of CO concentrations is drastically reduced, with concentration levels always under $4 \mu\text{g}/\text{m}^3$.

The quantitative results in

Table 35 support the improvement observed in the spatial maps. All four solution scenarios reduce the mean HC concentration relative to the reference scenario. The reduction increases progressively across the assessed scenarios, from 26.29% in SOL10 to 52.70% in SOL40.

Overall, the INDIGO solutions substantially reduce both the intensity and geographical spread of HC concentrations around the airport.

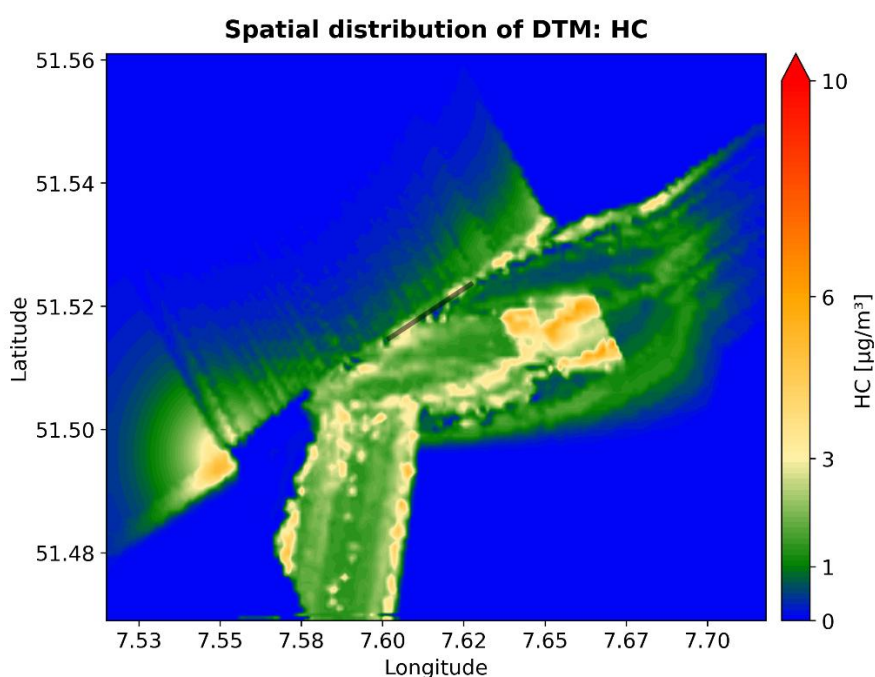


Figure 44: Figure 3: Spatial distribution of HC in DTM airport Reference scenario



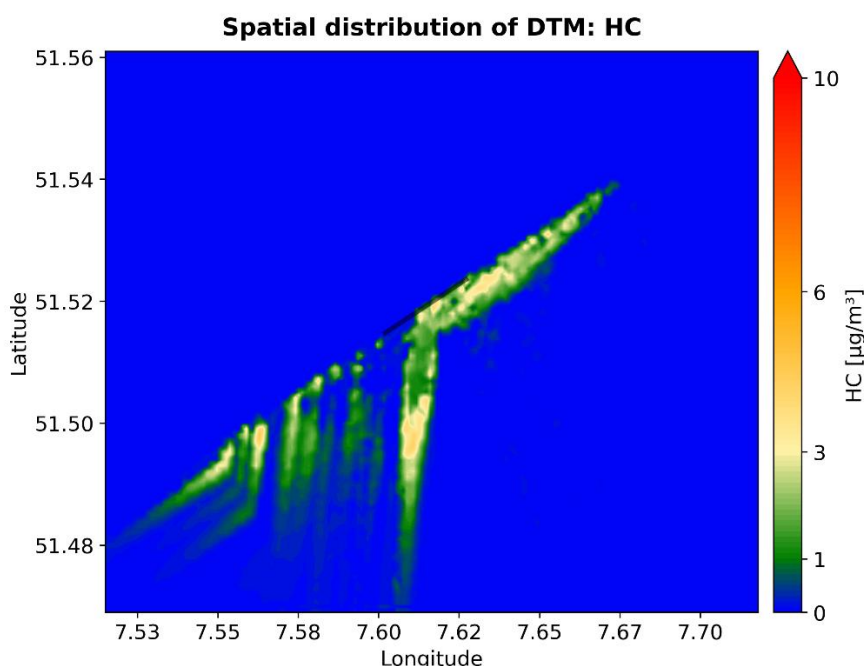


Figure 45: Spatial distribution of HC in DTM airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	26.29
SOL20	42.36
SOL30	47.69
SOL40	52.70

Table 35: Average reduction of HC daily mean concentration relative to DTM Reference scenario

NO_x

The spatial distribution of the daily mean concentration shows a substantial improvement in SOL40 compared with the reference scenario. In the reference scenario, concentrations are seen in Figure 46 above approximately $1 \mu\text{g}/\text{m}^3$ extend across a large part of the study area, with maximums located in the south and east with values around $4 \mu\text{g}/\text{m}^3$. Under SOL40, Figure 47 shows that both the magnitude and geographical extent of these concentrations decrease considerably. Number of peak concentrations is reduced, and their values do not exceed $4 \mu\text{g}/\text{m}^3$.

The quantitative results in Table 36 confirm reductions in the daily mean NO_x concentration for all four solution scenarios. The mean reduction increases progressively from 14.86% in SOL10 to 29.40% in SOL40. SOL40 therefore provides the greatest improvement, reducing the daily concentration by almost 30% relative to the reference scenario.



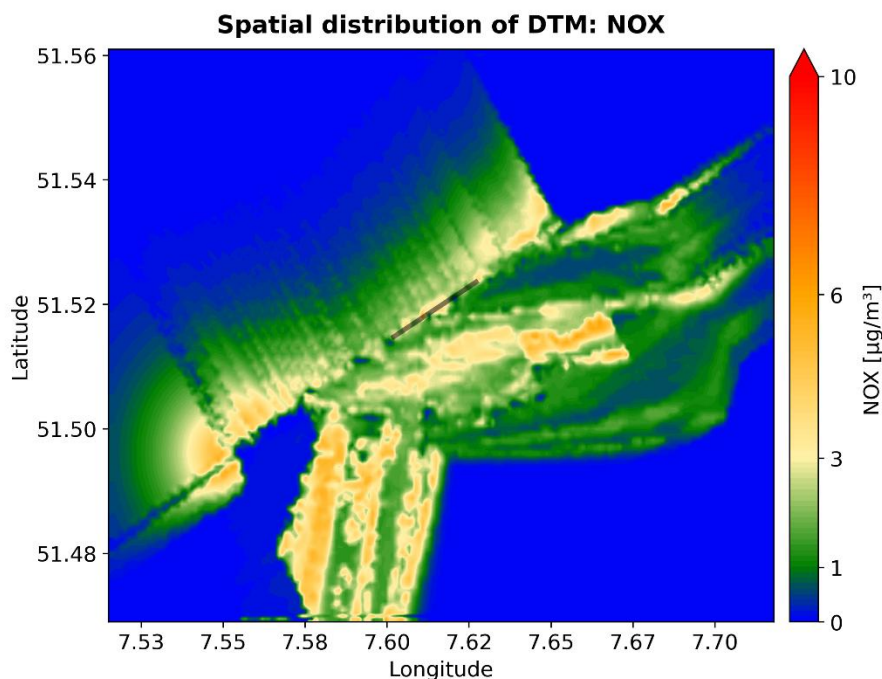


Figure 46: Spatial distribution of NOX in DTM airport Reference scenario

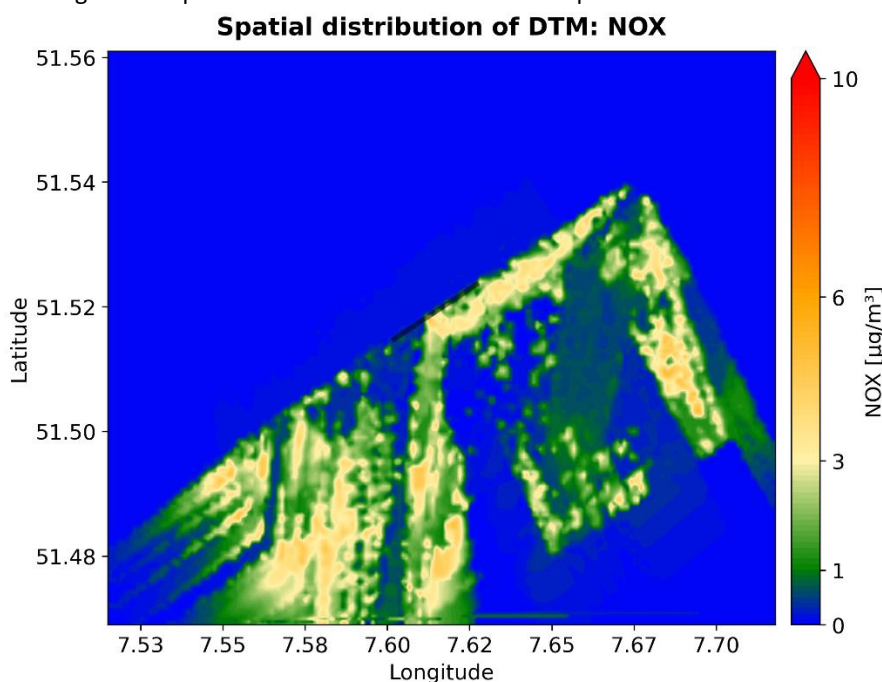


Figure 47: Spatial distribution of NOX in DTM airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	14.86
SOL20	24.01
SOL30	26.35
SOL40	29.40

Table 36: Average reduction of NOX daily mean concentration relative to DTM Reference scenario



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Regarding the metric NOX maximum hourly average concentration at receptor, spatial extension is not reduced in SOL40 compared with the reference scenario. However, severity of concentrations decreases: while it is observed in Figure 48 that in reference scenario many of them reach concentration values around $8 \mu\text{g}/\text{m}^3$, Figure 49 shows that in SOL40 most of them stay between $6 \mu\text{g}/\text{m}^3$ and $7 \mu\text{g}/\text{m}^3$.

The quantitative results confirm low and progressive reductions in this metric for all four solution scenarios, from 24.33% in SOL10 to 39.22% in SOL40, which therefore provides the greatest improvement.

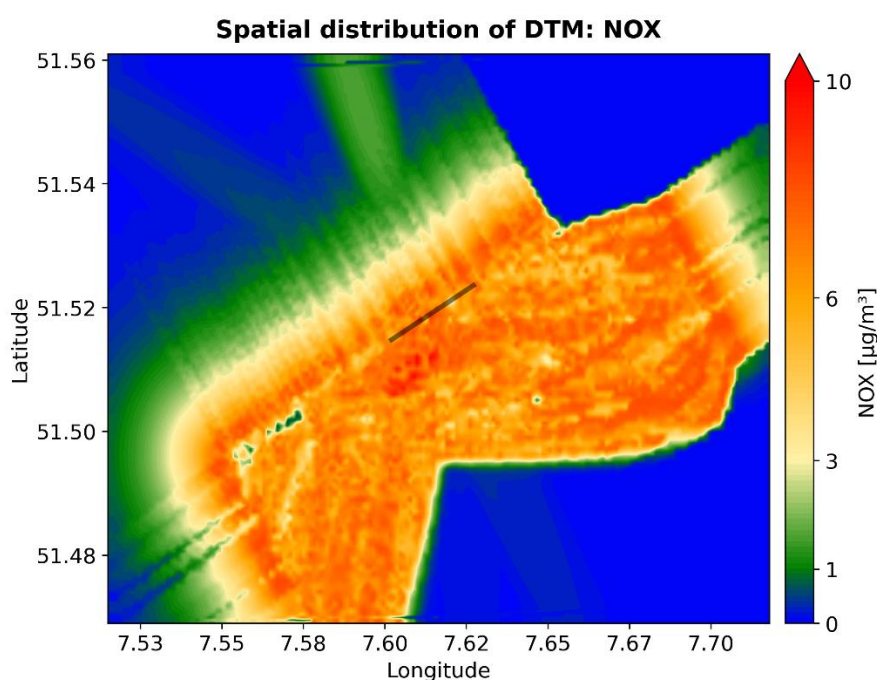


Figure 48: Spatial distribution of NOX maximum hourly average concentration at receptor in DTM airport Reference scenario



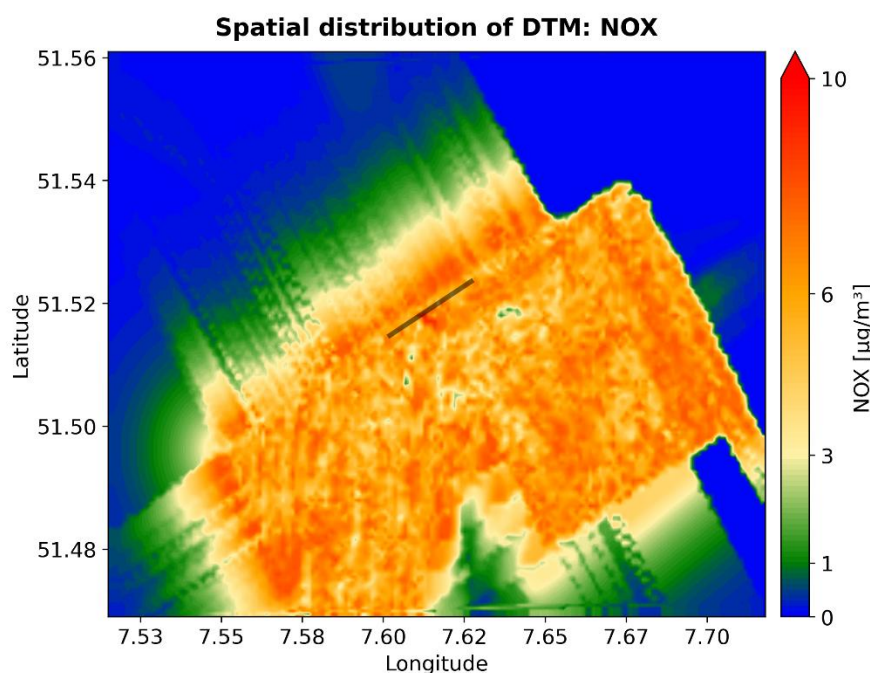


Figure 49: Spatial distribution of NOX maximum hourly average concentration at receptor in DTM airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	24.33
SOL20	38.15
SOL30	38.60
SOL40	39.22

Table 37: Average reduction of NOX maximum hourly average concentration at receptor relative to DTM reference scenario

PM

The comparison of the spatial distributions shows a substantial decrease in PM concentrations after applying INDIGO. In the reference scenario, Figure 50 shows that the most elevated concentrations are observed over the eastern area of the airport, reaching values of $3 \mu\text{g}/\text{m}^3$.

Under SOL40, according to Figure 51 spatial extent of PM concentrations decreases considerably, while intensity maintains with maximums of $3 \mu\text{g}/\text{m}$, changing their location to the south.

The quantitative results in Table 38 confirm the improvement observed in the spatial distributions. SOL10 produces a mean PM reduction of 14.27%, while SOL20 increases the reduction to 24.75% and SOL30 to 28.51%. SOL40 achieves the greatest reduction, almost a 33%. The results therefore show a progressive improvement from SOL10 to SOL40.



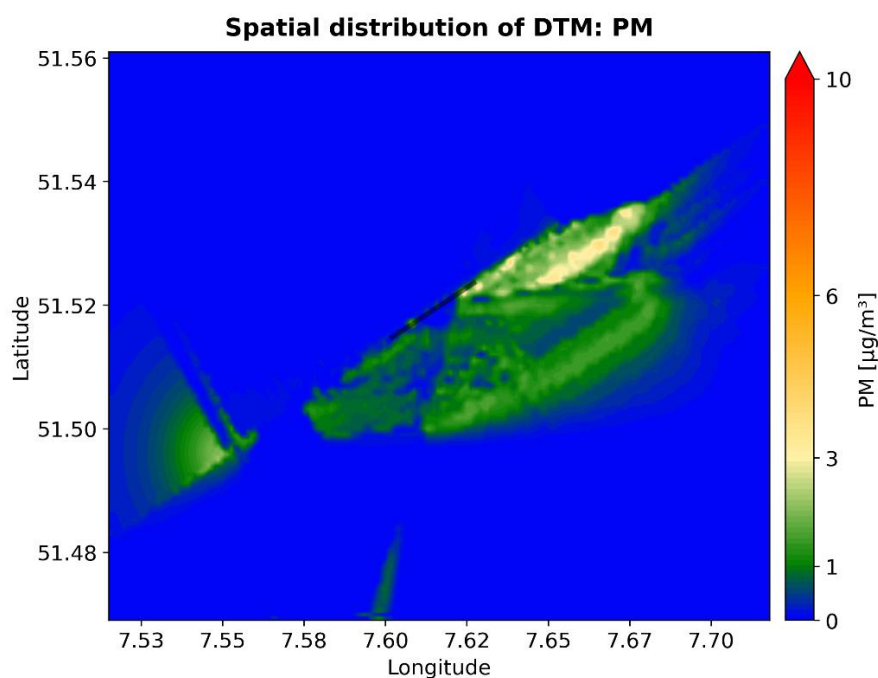


Figure 50: Spatial distribution of PM in DTM airport Reference scenario for the metric daily mean concentration

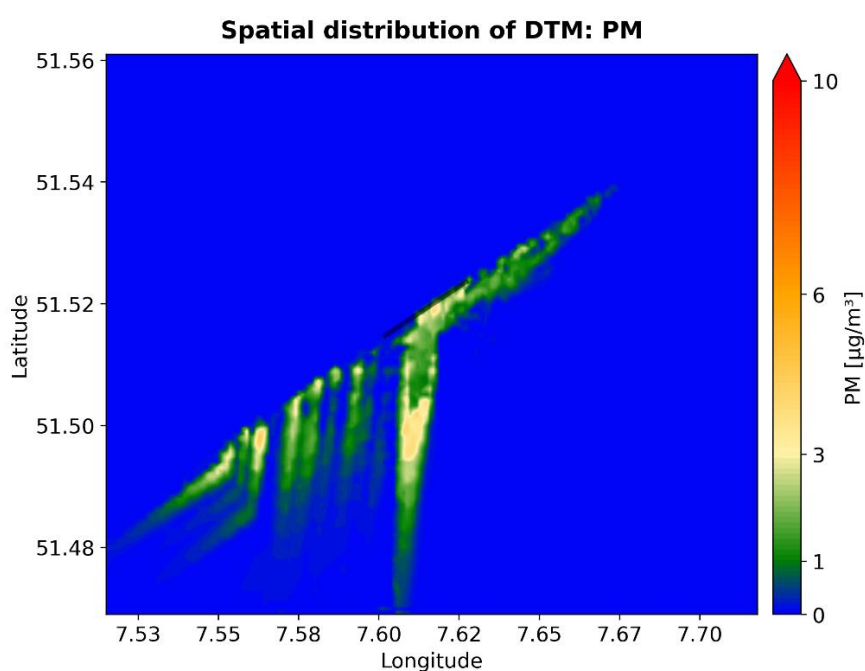


Figure 51: Spatial distribution of PM in DTM airport SOL40 scenario for the metric daily mean concentration



Scenario	Average reduction (%)
SOL10	14.27
SOL20	24.75
SOL30	28.51
SOL40	32.99

Table 38: Average reduction of PM day average concentration relative to DTM Reference scenario

BC

The spatial distributions show that BC concentrations are strongly concentrated around the airport infrastructure in all scenarios. In the reference scenario, as seen in Figure 52 pronounced maximums occur near the main airport emission sources, with concentration values of 10 ng/m³. It is remarkable how under SOL40 Figure 53 shows that maximums descend in severity, reaching most of them values of 6 ng/m³.

The quantitative results show an average BC reduction in all solution scenarios, progressing from the 14.45% decrease in SOL10 to the 33.14% in SOL40. Again, the results show a progressive improvement from SOL10 to SOL40.

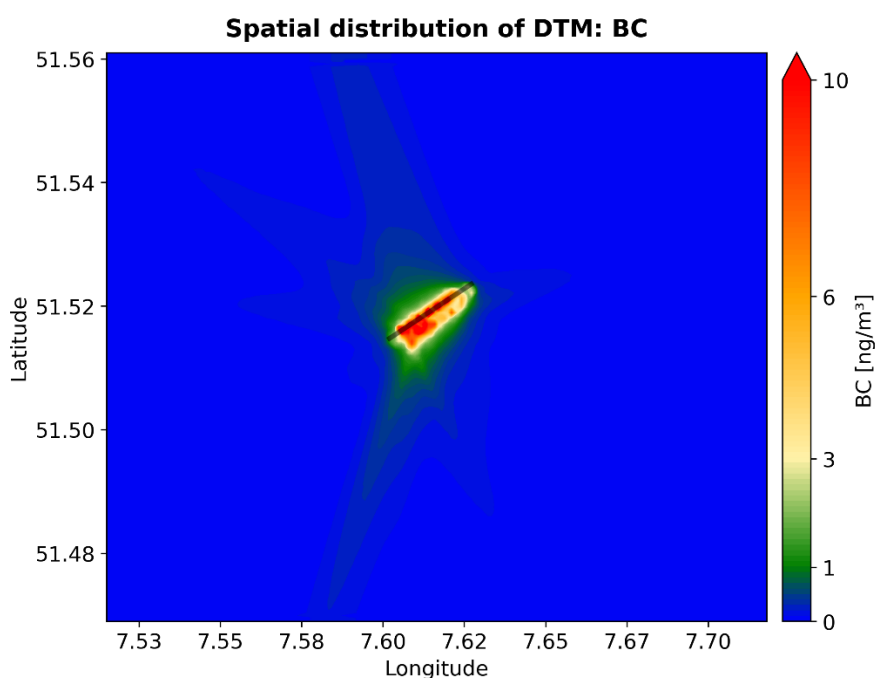


Figure 52: Spatial distribution of BC in DTM airport Reference scenario



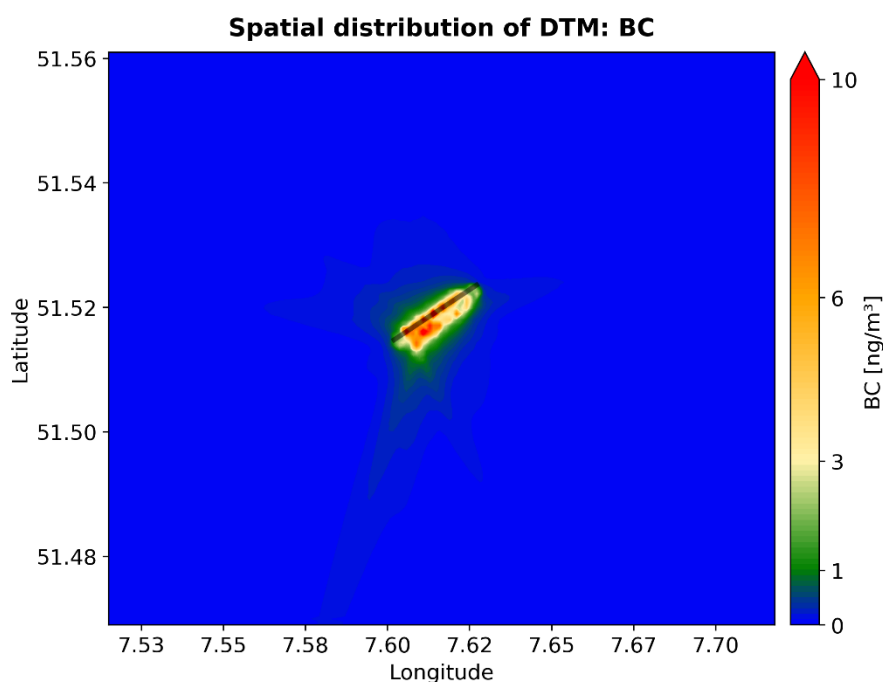


Figure 53: Spatial distribution of BC in DTM airport SOL40 scenario

Scenario	Mean reduction (%)
SOL10	14.45
SOL20	25.04
SOL30	28.67
SOL40	33.14

Table 39: Mean reduction of BC day average concentration relative to DTM Reference scenario

Conclusion

According to the summary presented in Table 40, the SOL40 scenario produces reductions for all pollutants considered, with mean improvements ranging from 29.40% to 52.70%. It is worth mentioning that, even though improvements are progressive for the different scenarios, from SOL10 increasing to reach the best values in SOL40, this evolution is not gradual. Some scenarios might increase faster than others, compared with the previous one. This happens, similar to RIX, because of the difficulty that supposes introducing INDIGO aircraft in traffic of this airport, following the replaceability and flyability rules (See Assumption 3 of Section 1).

Pollutants with the greatest reduction are CO and HC, with 52.69% and 52.70% respectively. BC, NOX and PM resulted in lower reductions, with values approximately between 29% and 39%.

Overall, these results indicate that SOL40 has a consistently positive effect on local air quality, reducing the concentrations of every pollutant assessed. The improvement is



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particularly pronounced for HC and CO, while the reductions in BC, PM and NO_x are more moderate but remain relevant.

Pollutant	Metric	Average Reduction under SOL40 (%)
CO	max. 8h	52.69
HC	daily mean	52.70
NOX	daily mean	29.40
NOX	Max. hourly	39.22
PM	daily mean	32.99
BC	daily mean	33.14

Table 40: Result summary SOL40 relative to DTM reference scenario

5.2.2.2. Noise

The results for Reference and Solution 40% scenarios are presented below:

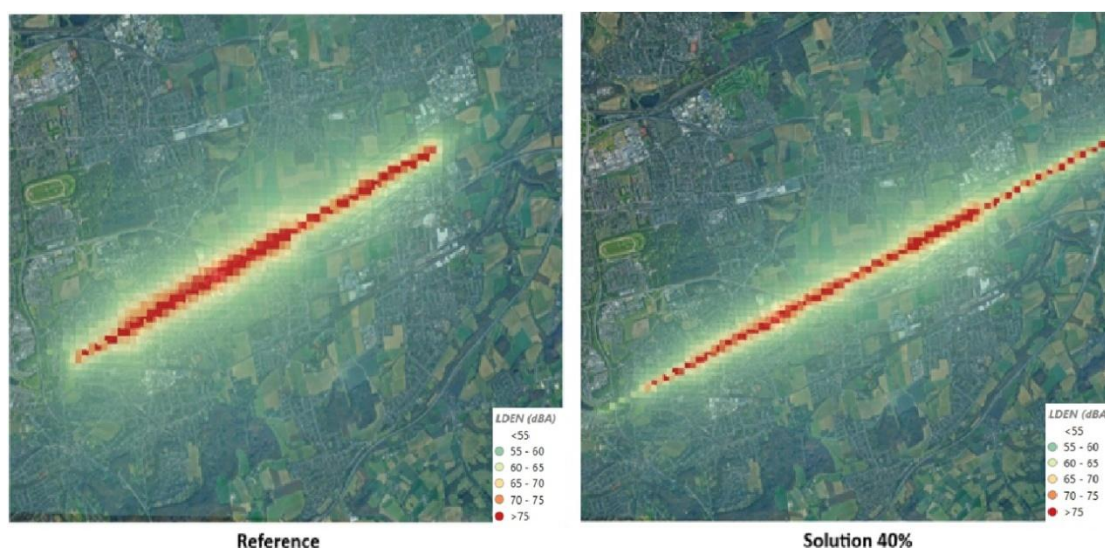


Figure 54. Comparison of LDEN results for Reference and Solution scenarios at DTM

As for the population exposed to more than 55 dB(A), the following table shows the results for each of the scenarios:



Scenario	Population exposed to more than 55 dBA (inhabitants)	Average reduction (%)
Reference	9372	-
Solution 10%	3873	59
Solution 20%	2988	68
Solution 30%	2515	73
Solution 40%	2201	77

Table 41. Population exposed in each scenario at DTM

Additionally, a spatial distribution of the population exposed is represented in the figure below:



Figure 55. Comparison of population exposed before (left) and after (right) INDIGO introduction at DTM

The results for Dortmund Airport show a substantial reduction in the population exposed to high levels of aircraft noise as the proposed solution increases. In the Reference scenario, 9372 inhabitants are exposed to noise levels above 55 dBA LDEN. This population decreases progressively to 2201 inhabitants under the scenario with the highest INDIGO replacement, corresponding to an overall reduction of 77%.

The intermediate solutions already provide significant reductions, with the exposed population decreasing by 59%, 68% and 73% for Solutions 10%, 20% and 30%, respectively. Therefore, although the absolute population affected is considerably lower than in Riga and other larger metropolitan cases analysed such as Madrid and Barcelona, the relative reduction achieved by the proposed solutions is particularly pronounced.

The spatial distribution of the results provides important context for the interpretation of these figures. Unlike the situations observed at Madrid and Barcelona (and, to a lesser extent, Riga), where large and relatively continuous urban areas are located within or close to the main noise corridors, the population potentially affected at Dortmund is more dispersed across the surrounding territory. The exposure maps show a number of smaller



population concentrations distributed along the main flight paths rather than a clearly defined densely populated urban area.

This characteristic is also noticeable when comparing the Reference and Solution 40% scenarios. In the Reference case, affected population is distributed across several locations along the noise footprint, with individual concentrations appearing at different points along the flight paths. In Solution 40%, these concentrations are substantially reduced, with many of the higher values disappearing or becoming considerably smaller. The overall spatial pattern remains identifiable, but the intensity of the population exposure is markedly reduced.

The relatively dispersed distribution of the affected population is an important characteristic of Dortmund UC. The airport's surrounding area includes several municipalities and settlements potentially affected by arriving and departing aircraft, rather than one dominant urban area. This means that the noise impact is distributed across a wider but less densely populated area, resulting in a different exposure pattern from that observed at the rest of airports assessed.

The results therefore demonstrate that the benefits of INDIGO at Dortmund are not primarily associated with removing a large continuous urban population from the noise footprint, but rather with reducing exposure across a number of small and spatially dispersed populated areas. This distinction is important because the number of inhabitants affected directly depends on the population distribution around each airport and should therefore be interpreted together with the spatial characteristics of the exposure.

Overall, INDIGO replacement reduces the population exposed to levels above 55 dBA LDEN by 77%, from 9372 to 2201 inhabitants. The maps confirm that this numerical reduction corresponds to a clear decrease in the intensity and concentration of population exposure along the main operational procedures.

5.2.3. Madrid airport

5.2.3.1. LAQ

LAQ results will be shown for each pollutant: figures with the spatial distribution of the pollutant concentration for both REF and SOL40 scenarios, followed by tables containing the benefit in LAQ achieved in different solution scenarios.

CO

The comparison of the spatial distributions shows a clear improvement in CO concentrations after applying the INDIGO solution. In the reference scenario (see Figure 56), elevated concentrations cover a relatively extensive area, with a pronounced peak close to the airport infrastructure and maximum values approaching $10 \mu\text{g}/\text{m}^3$. After the application of INDIGO (see Figure 57), this peak is substantially reduced, and the areas with moderate or high CO concentrations become smaller and more localized. Most of the study area consequently presents concentrations below approximately $1 \mu\text{g}/\text{m}^3$.



The analysis of the maximum 8-hour running average confirms that all four solution scenarios improve CO concentrations compared to the reference scenario. The average reduction (see Table 42) increases progressively from 24.17% in SOL10 to 34.72% in SOL20, 51.22% in SOL30 and 59.66% in SOL40. SOL40 therefore achieves the greatest improvement, reducing the maximum 8-hour running average CO concentration by approximately 60%.

Overall, the INDIGO solutions reduce both the magnitude and geographical extent of CO concentrations around the airport. Performance improves consistently from SOL10 to SOL40, with each successive scenario producing a greater average reduction than the previous one.

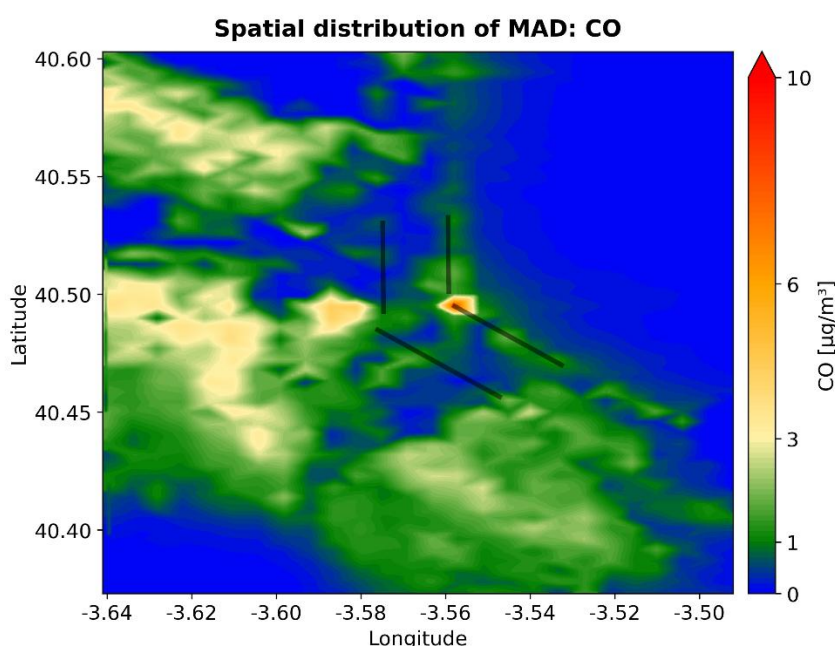


Figure 56: Spatial distribution of CO in MAD airport Reference scenario



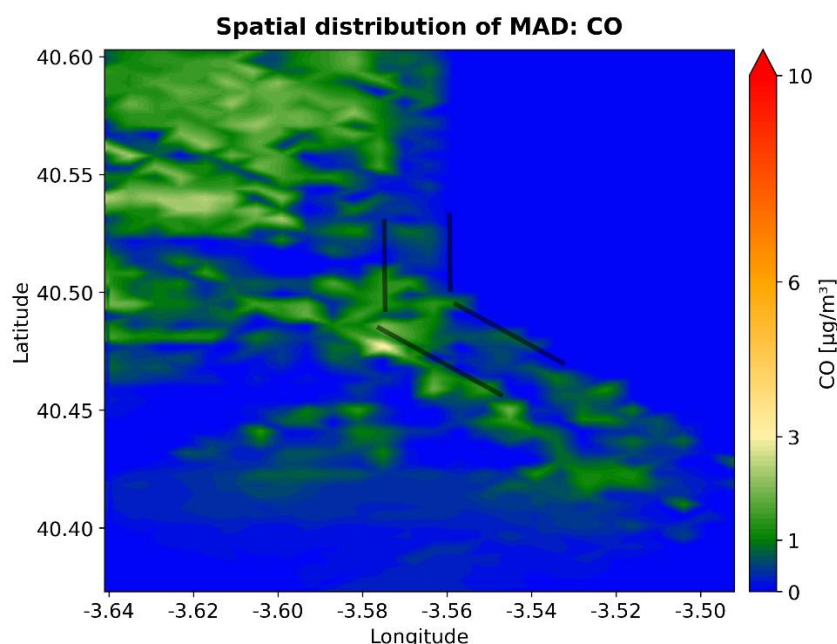


Figure 57: Spatial distribution of CO in MAD airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	24.17
SOL20	34.72
SOL30	51.22
SOL40	59.66

Table 42: CO 8-hour running average reduction relative to the reference scenario

HC

The comparison of the spatial distributions shows a substantial improvement in HC concentrations after applying INDIGO. In the reference scenario (see Figure 58), HC is distributed across a relatively large part of the study area, particularly to the west and south of the airport. Several zones present concentrations above approximately $1 \mu\text{g}/\text{m}^3$, with localized areas reaching around $3 \mu\text{g}/\text{m}^3$. After applying INDIGO (see Figure 59), both the magnitude and spatial extent of HC concentrations decrease considerably. The remaining concentrations are mainly confined to the immediate vicinity of the airport and a narrow dispersion corridor towards the southeast, while most of the study area presents values close to zero.

The quantitative results confirm the improvement observed in the spatial distributions. All four solution scenarios reduce mean HC concentrations relative to the reference scenario. The reduction increases (see Table 43) progressively from 24.82% in SOL10 to 35.37% in SOL20, 54.98% in SOL30 and 64.96% in SOL40. SOL40 therefore provides the greatest improvement, reducing the mean HC concentration by almost 65%.

Overall, the INDIGO solutions substantially reduce both the intensity and geographical spread of HC concentrations around the airport. The reduction in HC increases consistently



from SOL10 to SOL40, indicating progressively better performance across the four solution scenarios.

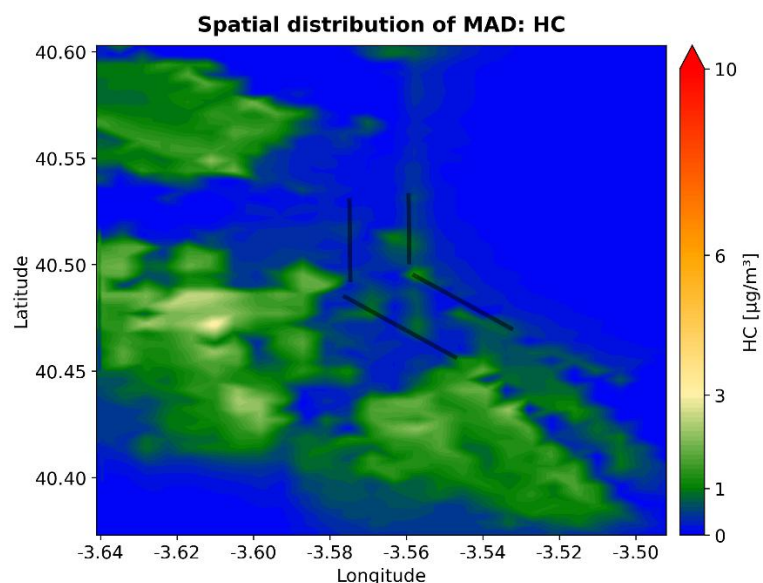


Figure 58: Spatial distribution of HC in MAD airport Reference scenario

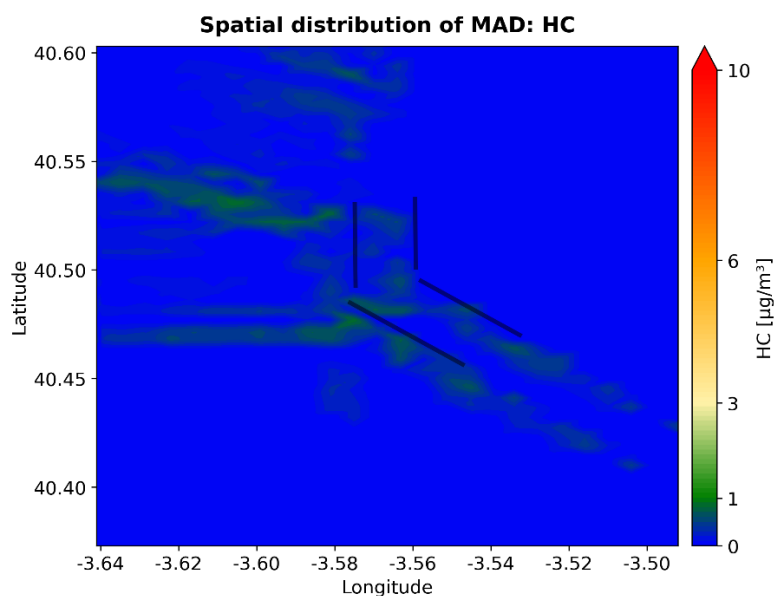


Figure 59: Spatial distribution of HC in MAD airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	24.82
SOL20	35.37
SOL30	54.98
SOL40	64.96

Table 43: Average reduction of HC daily mean concentration relative to the reference scenario



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NO_x

NO_x concentrations were assessed using two metrics: the daily mean concentration and the maximum hourly average concentration at each receptor.

For the daily mean concentration, the spatial comparison shows a clear improvement under SOL40 relative to the reference scenario. In the reference scenario (see Figure 60), elevated NO_x concentrations extend across a large area, particularly west and south of the airport. Under SOL40 (see Figure 61), both their magnitude and geographical extent decrease considerably. Most of the study area presents concentrations close to zero, while the remaining elevated values are more localized around the airport and in limited areas to the west and south.

The quantitative results confirm reductions in the daily mean concentration for all four solution scenarios. The average reduction (see Table 44) increases progressively from 15.08% in SOL10 to 20.63% in SOL20, 33.72% in SOL30 and 37.95% in SOL40. SOL40 therefore provides the greatest improvement, reducing the daily mean NO_x concentration by approximately 38% relative to the reference scenario.

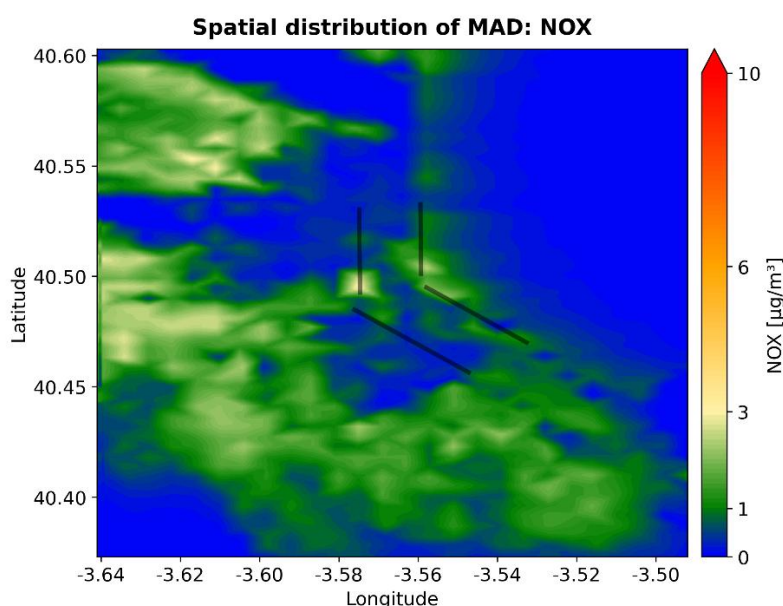


Figure 60: Spatial distribution of NO_x in MAD airport Reference scenario for the metric daily mean concentration



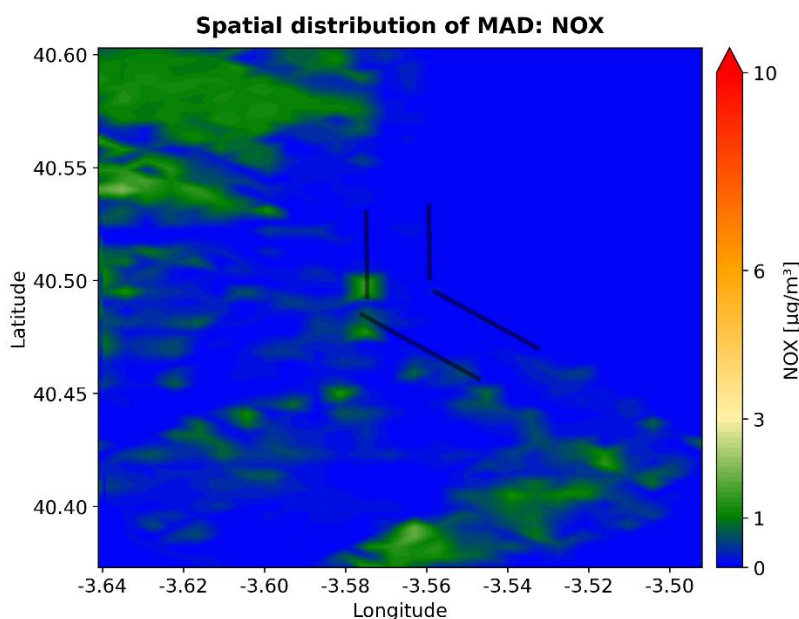


Figure 61: Spatial distribution of NO_x in MAD airport SOL40 scenario for the metric daily mean concentration

Scenario	Average reduction (%)
SOL10	15.08
SOL20	20.63
SOL30	33.72
SOL40	37.95

Table 44: Average reduction of NO_x daily mean concentration relative to the reference scenario

The maximum hourly average concentration also decreases under the INDIGO solutions. In the reference scenario (see Figure 62), elevated hourly concentrations are distributed across much of the study area, with pronounced peaks close to the airport infrastructure. Under SOL40 (see Figure 63), the affected area contracts considerably and concentrations decrease across most of the domain. Nevertheless, a localized maximum remains close to the airport, indicating that short-duration concentration peaks are reduced but not completely eliminated near the main emission sources.

The average reduction in the maximum hourly concentration (see Table 45) increases from 16.03% in SOL10 to 19.37% in SOL20, 29.88% in SOL30 and 36.06% in SOL40. As with the daily mean, SOL40 achieves the strongest improvement. The reductions in the two metrics are broadly comparable, although SOL40 produces a slightly greater reduction in the daily concentration (37.95%) than in the maximum hourly average concentration (36.06%).



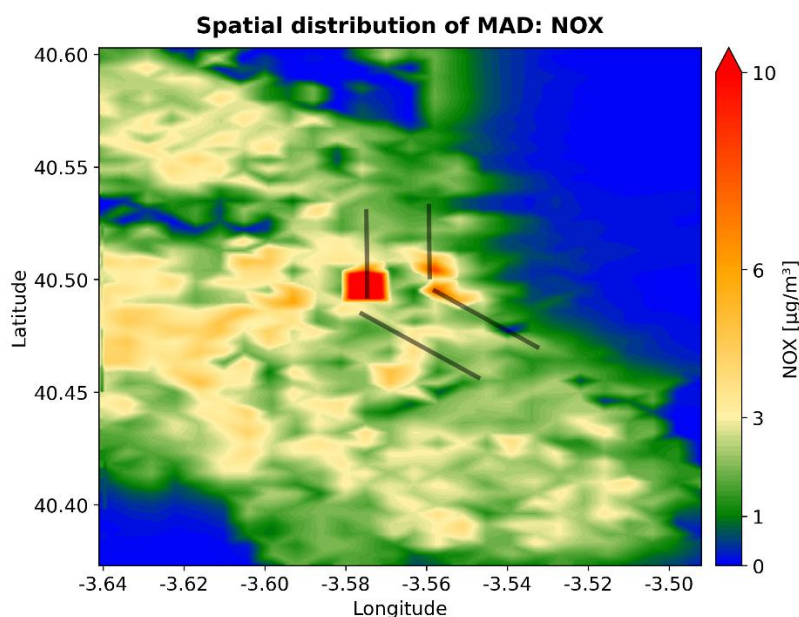


Figure 62: Spatial distribution of NO_x in MAD airport Reference scenario for the metric maximum hourly average concentration at receptor

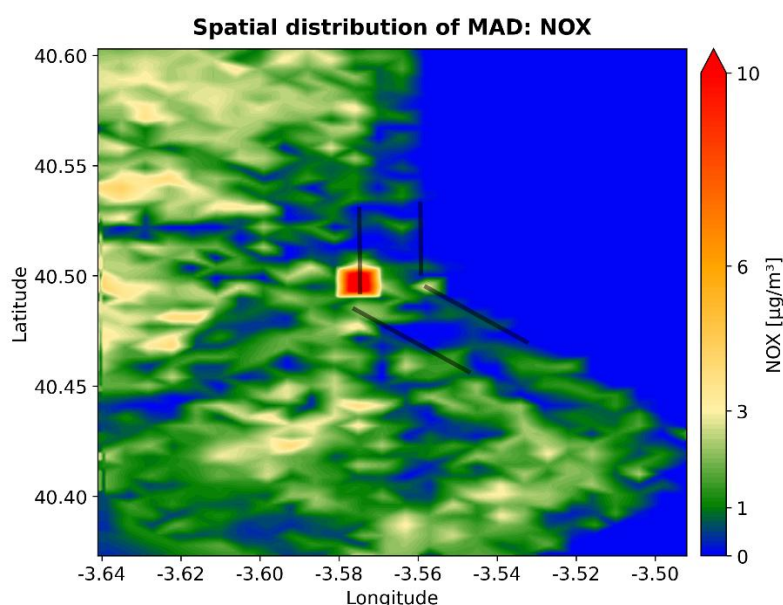


Figure 63: Spatial distribution of NO_x in MAD airport SOL40 scenario for the metric maximum hourly average concentration at receptor

Scenario	Average reduction (%)
SOL10	16.03
SOL20	19.37
SOL30	29.88
SOL40	36.06

Table 45: Average reduction of NO_x maximum hourly average concentration at receptor relative to the reference scenario



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PM

The comparison of the spatial distributions shows a substantial decrease in PM concentrations after applying INDIGO. In the reference scenario (see Figure 64), elevated concentrations are observed over several areas west and south of the airport. The most noticeable concentration zones are located southwest of the airport and along the southeastern dispersion corridor, with local values generally between approximately 1 and 3 $\mu\text{g}/\text{m}^3$.

Under SOL40 (see Figure 65), both the intensity and spatial extent of PM concentrations decrease considerably. Most of the study area presents concentrations close to zero, while the remaining elevated concentrations are more localized and mainly situated west of the airport and close to the airport infrastructure. The areas of increased concentration previously observed to the south and southwest are largely removed.

The quantitative results confirm reductions in mean PM concentrations for all four solution scenarios. The reduction increases (see Table 46) progressively from 16.65% in SOL10 to 24.58% in SOL20, 39.36% in SOL30 and 44.84% in SOL40. SOL40 therefore achieves the greatest improvement, although the additional reduction compared with SOL30 is relatively modest.

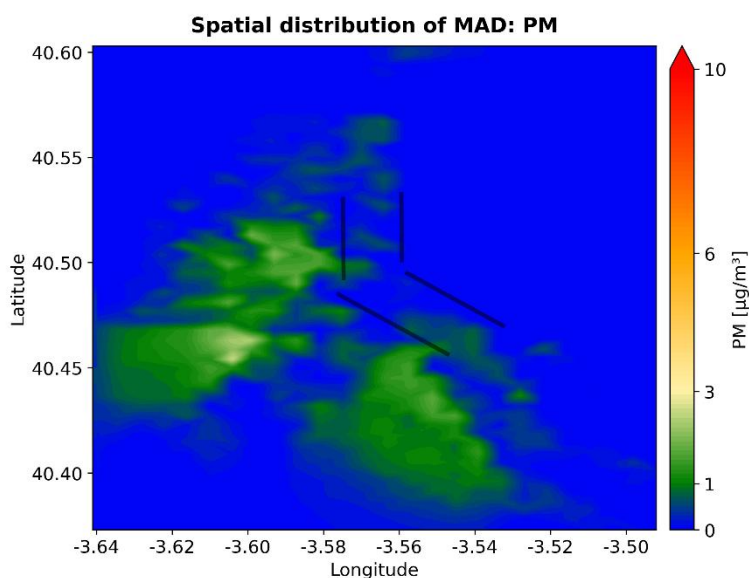


Figure 64: Spatial distribution of PM in MAD airport Reference scenario



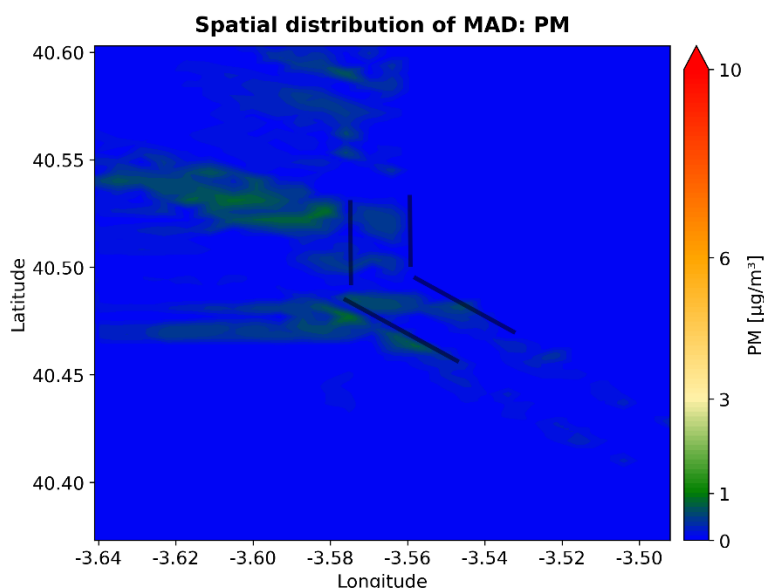


Figure 65: Spatial distribution of PM in MAD airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	16.65
SOL20	24.58
SOL30	39.36
SOL40	44.84

Table 46: Average reduction of PM daily mean concentration relative to the reference scenario

BC

The spatial distributions show that BC concentrations are strongly concentrated around the airport infrastructure. In the reference scenario (see Figure 66), pronounced peaks occur near the main airport emission sources, with the plume extending primarily towards the east and southeast. Under SOL40 (see Figure 67), the geographical extent and intensity of the surrounding plume decrease, particularly east of the airport. Nevertheless, localized maximums remain close to the airport infrastructure, suggesting that the highest BC concentrations continue to occur near the principal combustion-related emission sources.

The quantitative results confirm reductions in average BC concentrations for all four solution scenarios. The average reduction (see Table 47) increases progressively from 17.16% in SOL10 to 25.06% in SOL20, 39.94% in SOL30 and 45.42% in SOL40. SOL40 therefore provides the greatest improvement, reducing the average daily BC concentration by approximately 45% relative to the reference scenario.



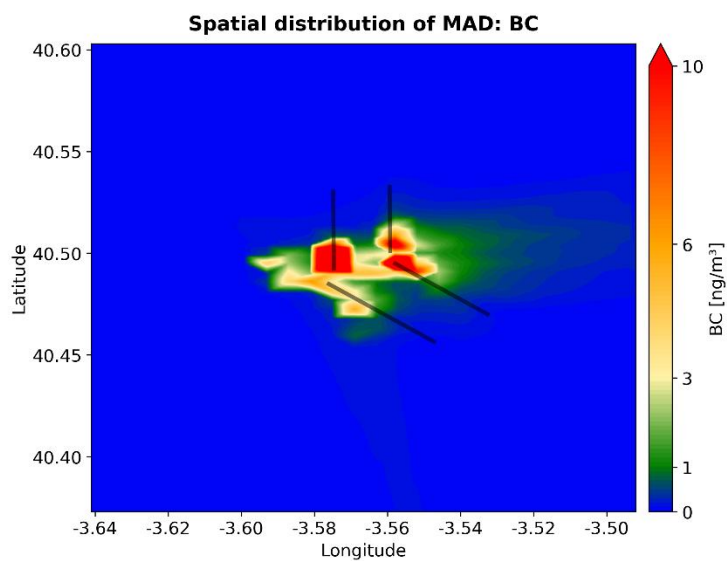


Figure 66: Spatial distribution of BC in MAD airport Reference scenario

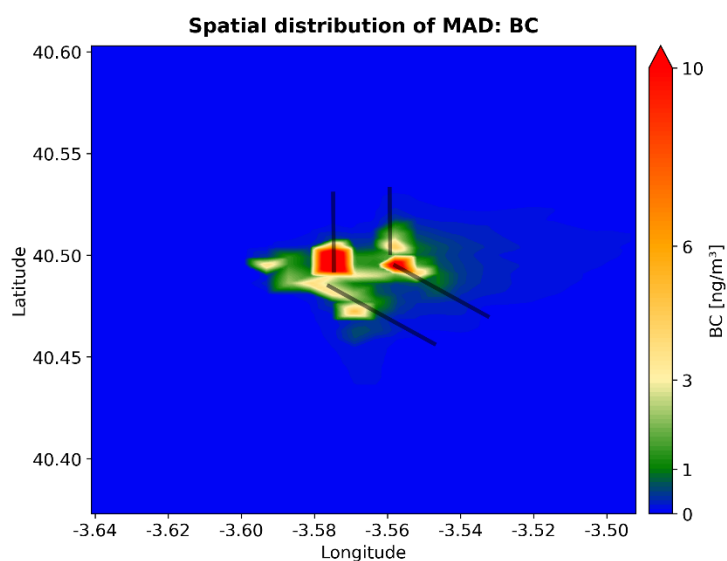


Figure 67: Spatial distribution of BC in MAD airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	17.16
SOL20	25.06
SOL30	39.94
SOL40	45.42

Table 47: Average reduction of BC daily mean concentration relative to the reference scenario

Conclusion



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

According to the summary presented in the Table 48, the SOL40 scenario produces reductions for all pollutants considered, with mean improvements ranging from 37.95% to 64.96%. The greatest reduction is observed for HC, at 64.96%, followed by CO, at 59.66%. BC and PM show similar improvements, with reductions of 45.42% and 44.84%, respectively. NO_x presents the smallest reduction, although its daily concentration still decreases substantially, by 37.95%.

Overall, these results indicate that SOL40 has a consistently positive effect on local air quality, reducing the concentrations of every pollutant assessed. The improvement is particularly pronounced for HC and CO, while the reductions in BC, PM and NO_x are more moderate but remain relevant.

Pollutant	Metric	Average Reduction under SOL40 (%)
CO	max. 8h	59.66
HC	daily mean	64.96
NOX	daily mean	37.95
NOX	Max. hourly	36.06
PM	daily mean	44.84
BC	daily mean	45.42

Table 48: Result summary SOL40 relative to the reference scenario

5.2.3.2. Noise

The results for Reference and Solution 40% scenarios are presented below:



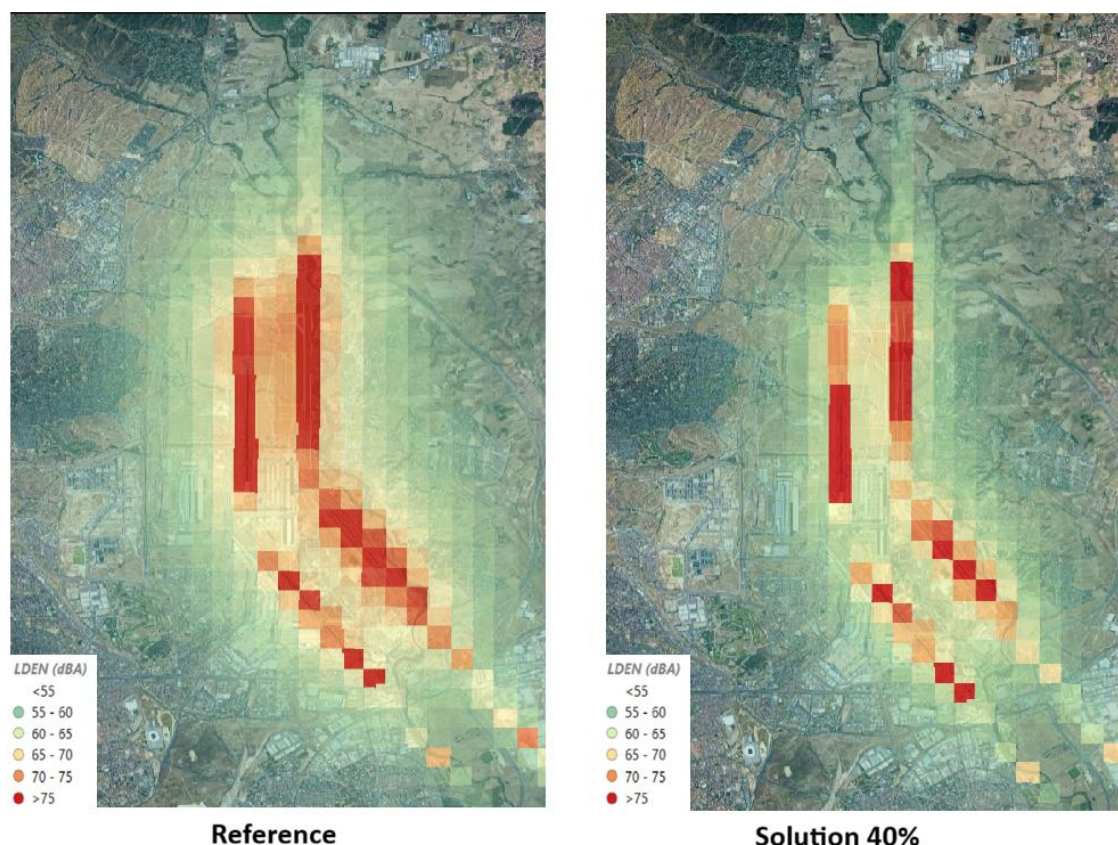


Figure 68. Comparison of LDEN results for Reference and Solution scenarios at MAD

As for the population exposed to more than 55 dB(A), the following table shows the results for each of the scenarios:

Scenario	Population exposed to more than 55 dBA (inhabitants)	Average reduction (%)
Reference	60423	-
Solution 10%	31718	47
Solution 20%	28264	53
Solution 30%	20438	66
Solution 40%	11471	81

Table 49. Population exposed in each scenario at MAD

Additionally, a spatial distribution of the population exposed is represented in the figure below:



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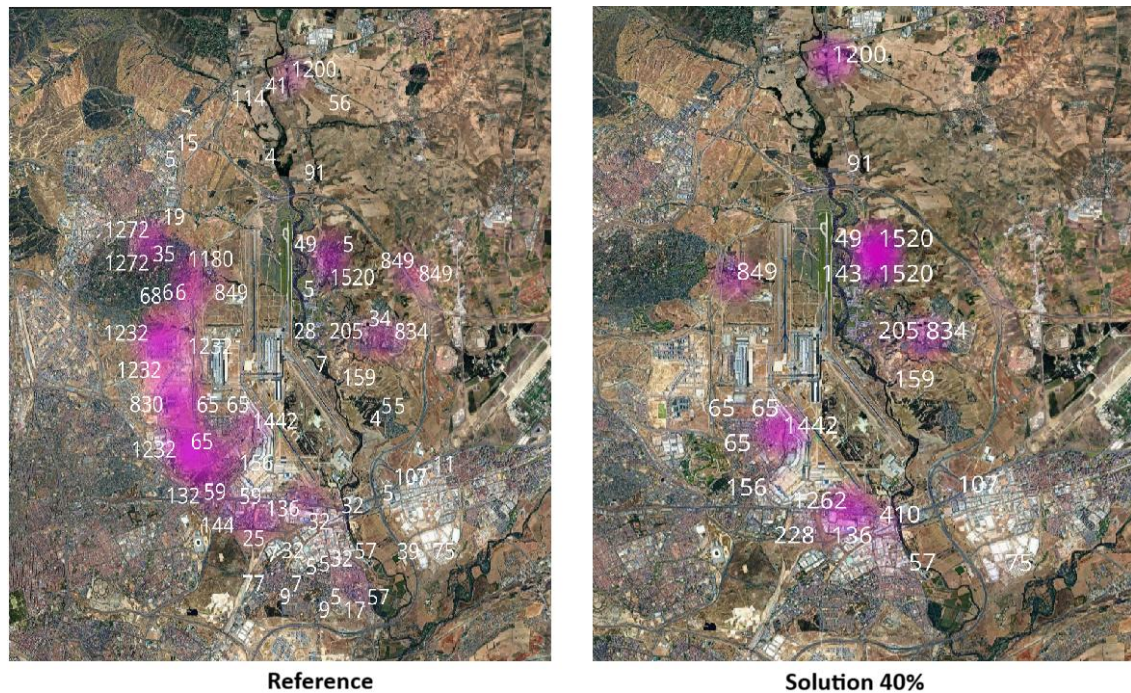


Figure 69. Comparison of population exposed before (left) and after (right) INDIGO introduction at MAD

The results for Madrid airport show a clear and progressive reduction in the population exposed to high levels of aircraft noise as the proposed solution increases. In the Reference scenario, 60423 inhabitants are exposed to noise levels above 55 dBA LDEN. This figure decreases progressively with the implementation of the different solutions, reaching 11471 inhabitants under Solution 40% scenario, which represents an overall reduction of 81%.

The intermediate solutions also provide substantial reductions, with the population exposed above 55 dBA decreasing by 47%, 53% and 66% for Solutions 10%, 20% and 30%, respectively. The particularly strong reduction obtained from Solution 30% onwards indicates that the higher solution levels have a significant effect on the areas experiencing the highest levels of aircraft noise (West side of the airport: Barajas and Alameda de Osuna neighbourhoods).

The spatial distribution of the LDEN results confirms this behaviour. In the Reference scenario, the highest noise levels are concentrated along the main airport runways and flight paths, generating several continuous areas with elevated noise levels. Under Solution 40% scenario, these high-noise areas become noticeably smaller and more discontinuous, particularly around the areas closest to the main flight paths. The most intense noise categories are substantially reduced, indicating a significant mitigation of the highest levels of aircraft noise.

The population distribution maps show a similar pattern. In the reference scenario, there is a considerable concentration of affected population throughout the areas surrounding the airport and the main flight corridors, with several locations showing relatively high numbers of inhabitants exposed. Under Solution 40% scenario, the number and concentration of these higher population values are clearly reduced. Although some localised areas of



exposure remain without significant reduction, the overall spatial extent of the population affected is considerably lower.

The magnitude of the reduction is particularly relevant in the Madrid UC because the baseline population exposed above 55 dBA is considerably larger than in the previous UCs (Riga and Dortmund). The implementation of INDIGO results in a substantial mitigation of high-level aircraft noise exposure in Madrid, with an 81% reduction in the population exposed above 55 dBA LDEN. The cartographic comparison supports the numerical results, showing a clear contraction of the areas subject to the highest noise levels and a marked reduction in the concentration of affected population.

5.2.4. Barcelona airport

5.2.4.1. LAQ

LAQ results will be shown for each pollutant: figures with the spatial distribution of the pollutant concentration for both REF and SOL40 scenarios, followed by tables containing the benefit in LAQ achieved in different solution scenarios.

CO

The comparison of the spatial distributions shows a clear reduction in CO concentrations at Barcelona Airport under the SOL40 scenario. In the reference scenario (see Figure 70), a pronounced high-concentration plume extends along a predominantly north–south axis through the airport area, with the highest concentrations located around the airport infrastructure. Additional dispersion corridors extend towards the northwest and east.

Under SOL40 (see Figure 71), the general spatial pattern remains similar, but the intensity and geographical extent of the elevated concentrations decrease. The central peak becomes smaller and more localised, while concentrations along the northern and southern sections of the plume are reduced. Lower concentrations are also observed across much of the surrounding area, although some elevated values remain close to the airport infrastructure.

The quantitative analysis of the maximum 8-hour running average confirms reductions in all four solution scenarios. The average reduction increases from 8.96% in SOL10 to 22.96% in SOL20, 27.35% in SOL30 and 35.75% in SOL40. SOL40 therefore provides the greatest improvement, reducing the maximum 8-hour running average CO concentration by approximately 36% relative to the reference scenario.

Overall, the INDIGO solutions reduce both the magnitude and spatial extent of CO concentrations around Barcelona Airport. Performance improves across the four scenarios, with SOL40 delivering the greatest benefit, although localised areas of elevated concentration remain close to the airport's principal emission sources.



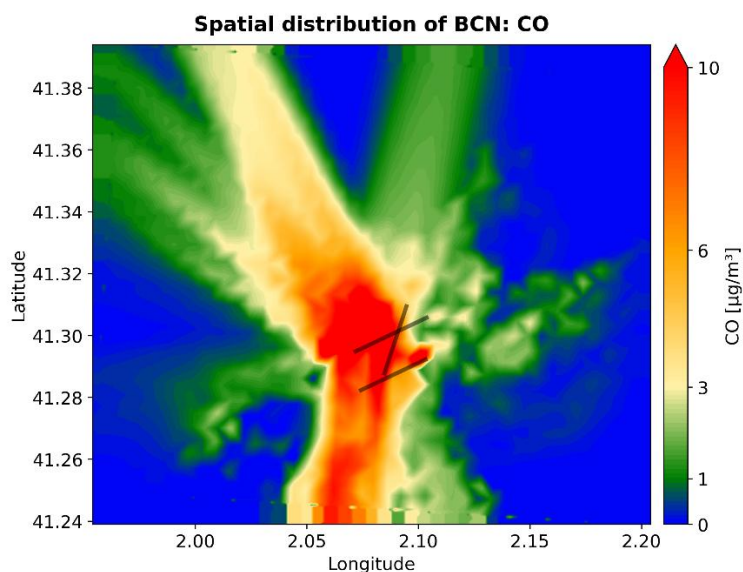


Figure 70: Spatial distribution of CO in BCN airport reference scenario

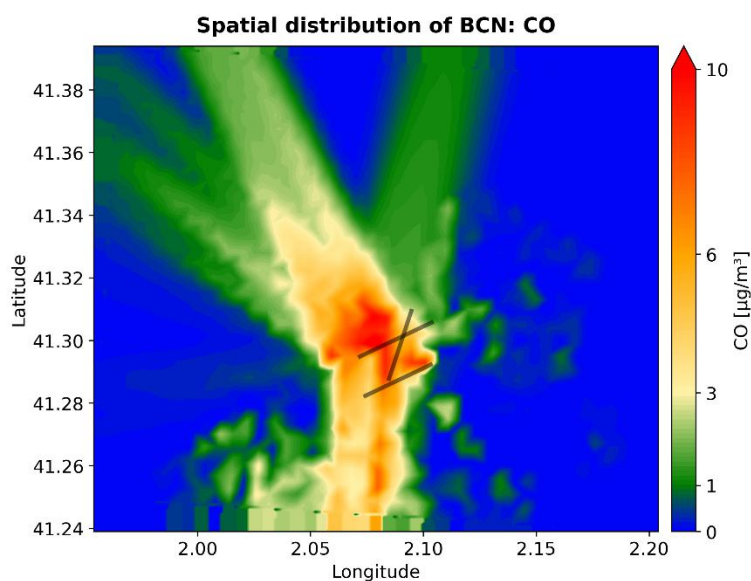


Figure 71: Spatial distribution of CO in BCN airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	8.96
SOL20	22.96
SOL30	27.35
SOL40	35.75

Table 50: CO 8-hour running average reduction relative to the reference scenario



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HC

The comparison of the spatial distributions shows a substantial reduction in HC concentrations at Barcelona Airport under the SOL40 scenario. In the reference scenario, elevated concentrations extend across a relatively broad area around the airport, particularly towards the south, southwest and east. Several localised areas of moderate concentration are also visible near the airport infrastructure and along the principal dispersion corridors.

Under SOL40, both the intensity and geographical extent of HC concentrations decrease considerably. Most of the study area presents concentrations close to zero, while the remaining elevated values are confined mainly to the immediate airport area and a narrow corridor extending southwards. The localised concentration areas observed to the southwest and east in the reference scenario are also substantially reduced.

The quantitative results confirm reductions in daily mean HC concentrations for all four solution scenarios. The average reduction is already substantial under SOL10, at 54.04%, and increases to 59.78% in SOL20, 63.04% in SOL30 and 66.44% in SOL40. SOL40 therefore provides the greatest improvement, reducing the average daily HC concentration by approximately two-thirds relative to the reference scenario.

The average reduction increases from 54.04% in SOL10 to 59.78% in SOL20, 63.04% in SOL30, and 66.44% in SOL40. However, the reduction is not directly proportional to the percentage of INDIGO flights introduced. This non-linear behaviour is associated with the difficulty of integrating INDIGO aircraft into Barcelona Airport traffic while complying with the replaceability and flyability rules described in Assumption 3 of Section 1. Consequently, each additional group of INDIGO flights may have different operational and emissions characteristics, and therefore does not necessarily produce an equivalent reduction in HC concentrations.

Overall, the INDIGO solutions substantially reduce both the magnitude and spatial extent of HC concentrations around Barcelona Airport. Although performance continues to improve from SOL10 to SOL40, the results show diminishing additional reductions at higher levels of INDIGO implementation.



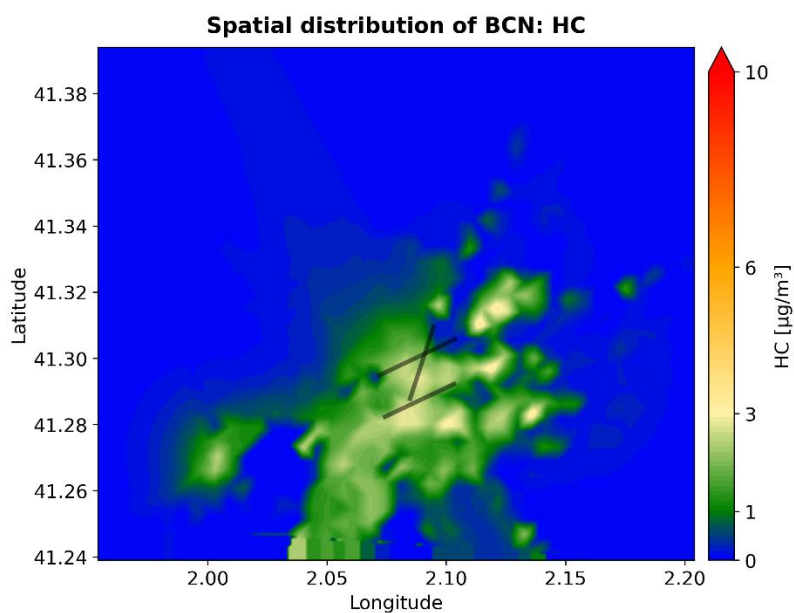


Figure 72: Spatial distribution of HC in BCN airport reference scenario

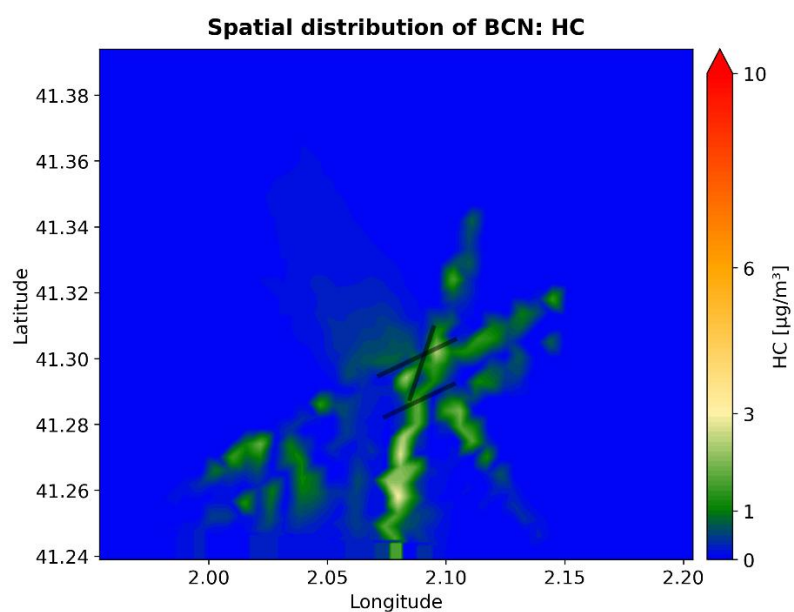


Figure 73: Spatial distribution of HC in BCN airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	54.04
SOL20	59.78
SOL30	63.04
SOL40	66.44

Table 51: Average reduction of HC daily mean concentration relative to the reference scenario



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NO_x

Figure 74 and Figure 75 compare the spatial distribution of the NO_x daily mean concentration for the reference and SOL40 scenarios. The reference scenario (see Figure 74) presents an extensive area of high concentrations along the main flight corridors and around the airport, with several areas reaching or exceeding the upper limit of the colour scale (10 µg/m³). Under SOL40 (see Figure 75), both the magnitude and spatial extent of these concentrations decrease substantially. The highest remaining concentrations are mainly confined to a narrower area south of the airport, while much of the surrounding domain shows concentrations below approximately 1–3 µg/m³.

As shown in

Table 52, the average reduction in daily mean NO_x concentration is already 50.65% under SOL10 and increases slightly to 51.75% under SOL20, 52.34% under SOL30, and 53.27% under SOL40. Therefore, most of the reduction is achieved when the first 10% of flights are operated by INDIGO aircraft, while the additional improvements associated with subsequent scenarios are comparatively limited.

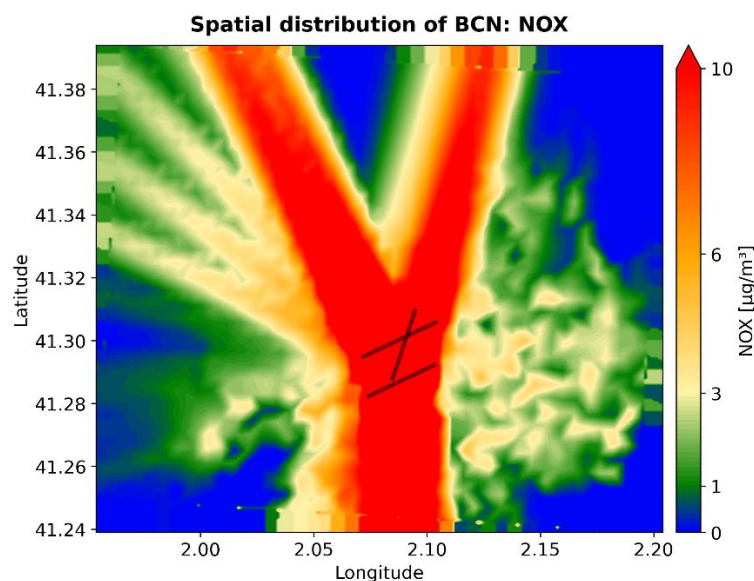


Figure 74: Spatial distribution of NO_x in BCN airport Reference scenario for the metric daily mean concentration



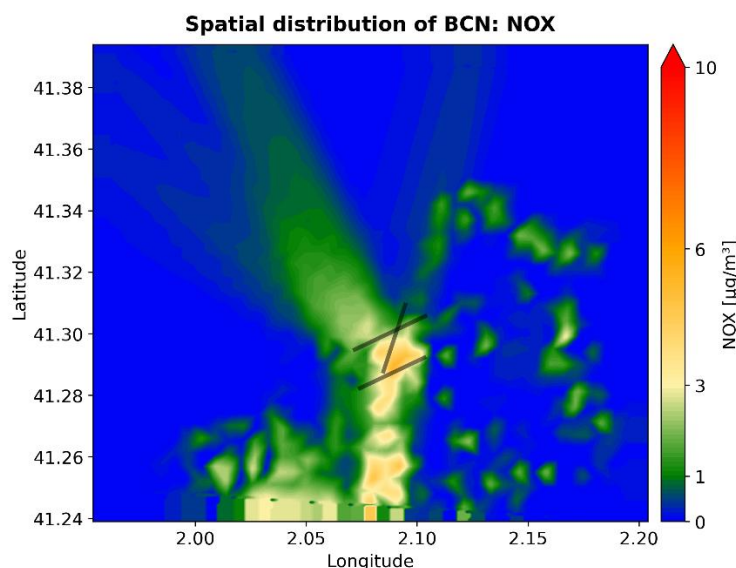


Figure 75: Spatial distribution of NO_x in BCN airport SOL40 scenario for the metric daily mean concentration

Scenario	Average reduction (%)
SOL10	50.65
SOL20	51.75
SOL30	52.34
SOL40	53.27

Table 52: Average reduction of NO_x daily mean concentration relative to the reference scenario

Figure 76 and Figure 77 show the maximum hourly average NO_x concentration at each receptor. For this metric, the spatial differences between the reference and SOL40 scenarios are less pronounced than for the daily mean concentration. High hourly concentrations remain visible along the main flight corridors in SOL40, although reductions are observed in some peripheral areas. The average reduction (see

Table 53) increases from 3.88% in SOL10 to 5.38% in SOL20, 8.14% in SOL30, and 8.99% in SOL40.

The reductions are not directly proportional to the percentage of INDIGO flights introduced. This non-linear behavior is associated with the difficulty of integrating INDIGO aircraft into Barcelona Airport traffic while complying with the replaceability and flyability rules described in Assumption 3 of Section 1. Consequently, each additional group of INDIGO flights may have different operational and emission characteristics and does not necessarily produce an equivalent reduction in NO_x concentrations.



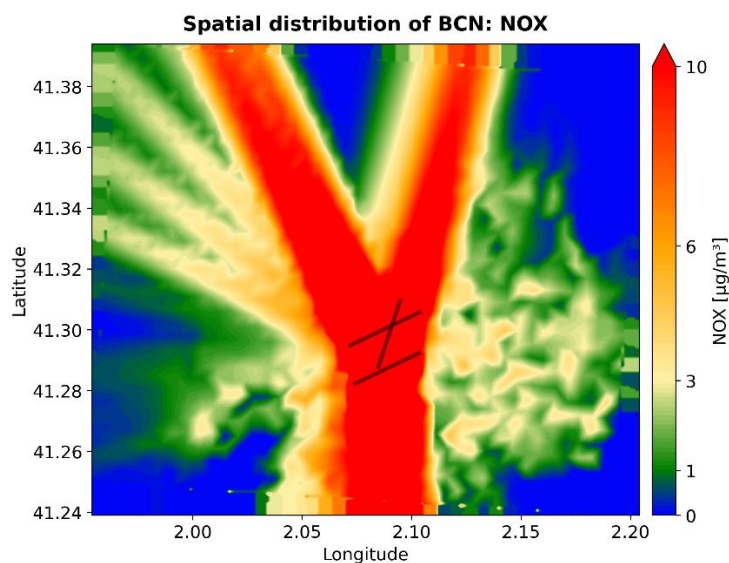


Figure 76: Spatial distribution of NO_x in BCN airport reference scenario for the metric maximum hourly average concentration at receptor

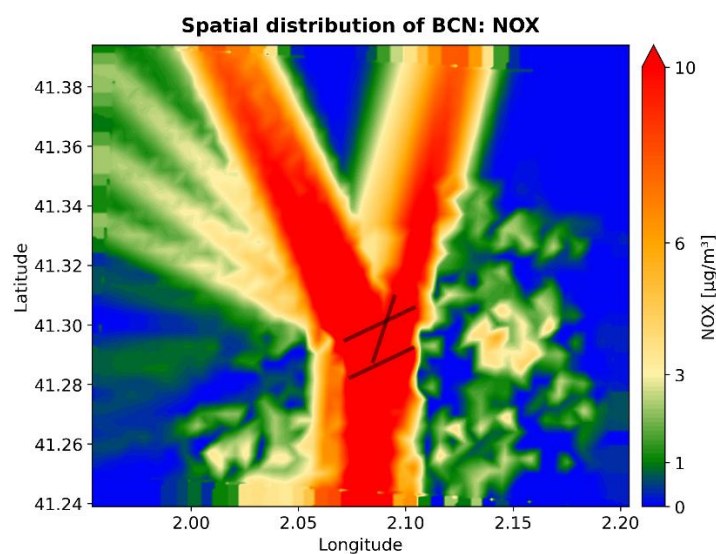


Figure 77: Spatial distribution of NO_x in BCN airport SOL40 scenario for the metric maximum hourly average concentration at receptor

Scenario	Average reduction (%)
SOL10	3.88
SOL20	5.38
SOL30	8.14
SOL40	8.99

Table 53: Average reduction of NO_x maximum hourly average concentration at receptor relative to the reference scenario



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The marked difference between the reductions obtained for the two NO_x metrics may be explained by their different temporal characteristics. The daily mean concentration accounts for reductions occurring throughout the entire day; therefore, the lower emissions produced by INDIGO aircraft have a cumulative effect on this metric. In contrast, the maximum hourly average concentration at each receptor is determined by a single peak hour and is consequently more sensitive to the specific flights operating during that hour. If the peak is mainly associated with conventional aircraft, or if the INDIGO flights do not operate at the time and location responsible for the maximum concentration, the hourly maximum may remain relatively high. Therefore, even though the number of flights, schedules, and meteorological conditions remain unchanged, replacing the emissions of selected flights can substantially reduce the daily mean concentration without producing an equivalent reduction in the maximum hourly concentration.

It should also be highlighted that, although the NO_x emission rate (see section 3.3.2) during the taxi phase is higher in the solution scenarios than in the reference scenario, an overall reduction in NO_x concentration is still observed. This improvement is mainly attributable to the substantially lower NO_x emission rates during the airborne phases of flight. The reductions achieved during these phases are sufficient to offset the increase in taxi-related emissions, resulting in a noticeable overall reduction in NO_x concentrations.

PM

Figures 78 and 79 compare the spatial distribution of the daily mean particulate matter (PM) concentration in the reference and SOL40 scenarios. In the reference scenario (see Figure 78), the highest concentrations are located around the airport and extend mainly towards the south-west and south. Under SOL40 (see Figure 79), both the magnitude and spatial extent of PM concentrations decrease considerably. The remaining concentrations are primarily confined to a narrower area around and south of the airport, while most of the study domain presents values below approximately $1 \mu\text{g}/\text{m}^3$.

According to Table 54, the average reduction in daily mean PM concentration is 52.19% under SOL10 and increases to 57.36% under SOL20. The reduction remains almost unchanged under SOL30, at 57.27%, before increasing to 60.07% under SOL40. These results demonstrate that the introduction of INDIGO aircraft produces a substantial overall reduction in PM concentrations, although the improvement is not proportional to the percentage of INDIGO flights included in each scenario. The absence of a proportional increase across the scenarios may be associated with the difficulty of integrating INDIGO aircraft into Barcelona Airport traffic while complying with the replaceability and flyability rules described in Assumption 3 of Section 1.



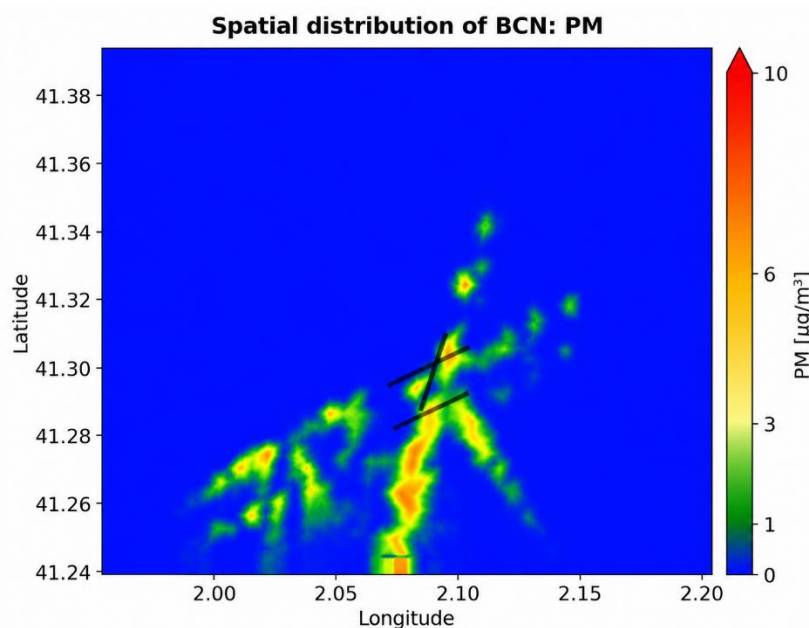


Figure 78: Spatial distribution of PM in BCN airport reference scenario

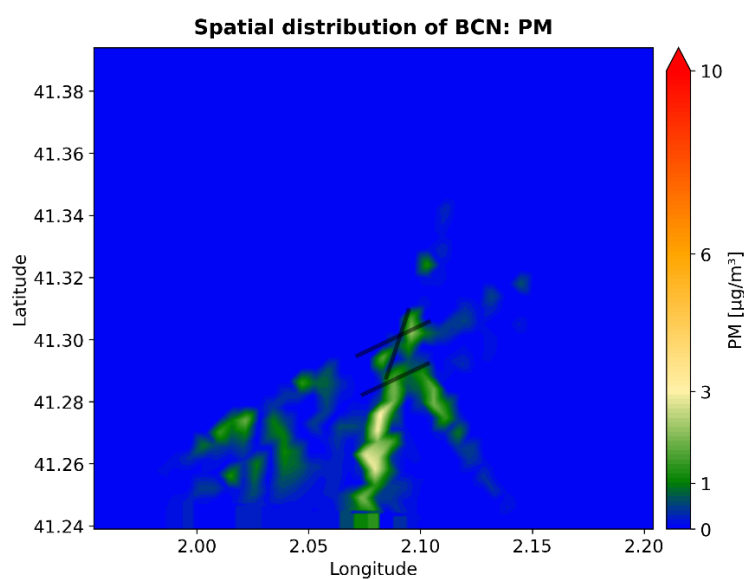


Figure 79: Spatial distribution of PM in BCN airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	52.19
SOL20	57.36
SOL30	57.27
SOL40	60.07

Table 54: Average reduction of PM daily mean concentration relative to the reference scenario



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BC

Figure 80 and Figure 81 compare the spatial distribution of the daily mean black carbon (BC) concentration in the reference and SOL40 scenarios. BC concentrations are expressed in ng/m^3 because black carbon is a specific component of particulate matter and is generally present at much lower mass concentrations than total particulate matter. The use of nanograms per cubic metre therefore provides a more appropriate scale for representing its concentration.

In the reference scenario (see Figure 80), an extensive area of high BC concentration is visible along the principal flight corridors and around the airport. Under SOL40 (see Figure 81), the spatial extent of the highest concentrations decreases, particularly in the north-western part of the study area, where a transition from red to orange, yellow, and green is observed. Nevertheless, high concentrations remain along the main north-south corridor. Since both maps are limited to an upper value of $10 \text{ ng}/\text{m}^3$, areas shown in red may represent concentrations equal to or greater than this value. Consequently, the visual comparison alone may not fully capture the magnitude of the reduction in the most highly affected areas.

According to Table 55, the average reduction in daily mean BC concentration is 52.19% under SOL10, increasing to 57.36% under SOL20. The reduction remains almost unchanged under SOL30, at 57.27%, before increasing to 61.14% under SOL40. The absence of a proportional increase across the scenarios may be associated with the difficulty of integrating INDIGO aircraft into Barcelona Airport traffic while complying with the replaceability and flyability rules described in Assumption 3 of Section 1. Consequently, each additional group of INDIGO flights may have different operational and emission characteristics and may not operate during the periods or along the trajectories that contribute most strongly to BC concentrations.

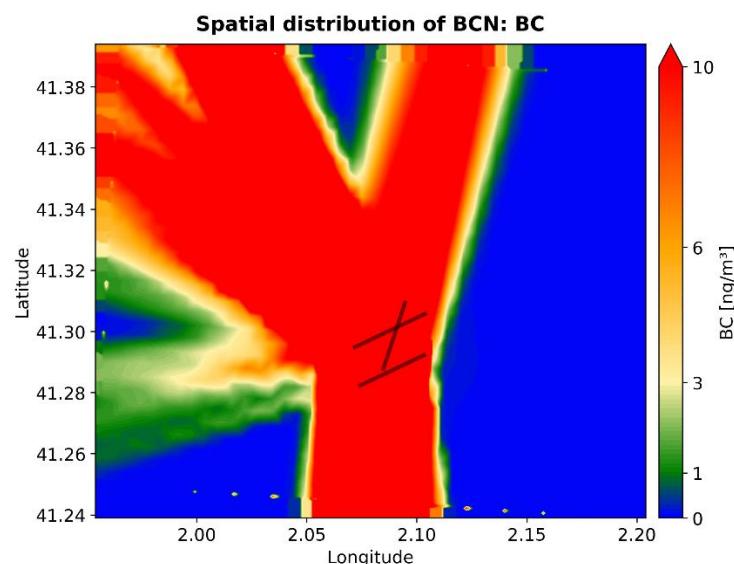


Figure 80: Spatial distribution of BC in BCN airport reference scenario



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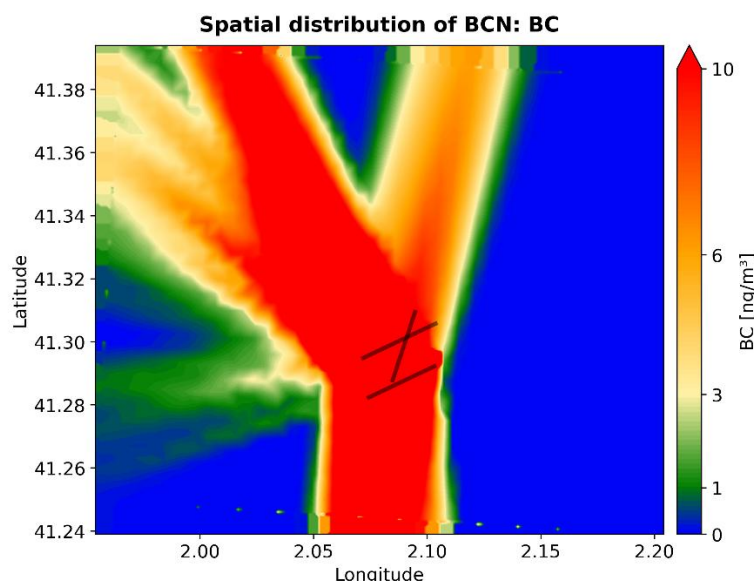


Figure 81: Spatial distribution of BC in BCN airport SOL40 scenario

Scenario	Average reduction (%)
SOL10	52.19
SOL20	57.36
SOL30	57.27
SOL40	61.14

Table 55: Average reduction of BC daily mean concentration relative to the reference scenario

Conclusion

According to the summary Table 56, the SOL40 scenario produces reductions for all the pollutants and metrics assessed at Barcelona Airport. The largest reduction is obtained for the daily mean HC concentration, at 66.44%, followed by BC at 61.14%, PM at 60.07%, and the daily mean NO_x concentration at 53.27%. The maximum 8-hour average CO concentration decreases by 35.75%. By contrast, the maximum hourly average NO_x concentration presents a considerably lower reduction of 8.99%, indicating that the INDIGO solution has a stronger effect on average daily exposure than on short-term NO_x concentration peaks. It is also notable that for Barcelona airport, the pollutants with highest reductions are HC, BC and PM, above 60%, while in other airports the HC and CO were the most reduced pollutants, this may be a particularity of Barcelona airport under traffic and scenario design, as well as airport/terminal configurations (e.g. larger taxi distances), to be further studied.

A particular feature of the Barcelona results is that substantial reductions in daily mean concentrations are already achieved under SOL10. HC, NO_x, PM, and BC decrease by approximately 50% or more when only 10% of the eligible flights are replaced by INDIGO aircraft. However, increasing the proportion of INDIGO flights from 10% to 40% produces comparatively limited additional improvements for these pollutants. This behaviour differs from that observed at the other airports analysed, where the reductions generally increase more progressively as the proportion of INDIGO flights increases.



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

One possible explanation is related to the operational characteristics of Barcelona Airport. Taxi distances are generally longer than at the other airports considered, while INDIGO aircraft have lower taxi-phase emission rates than conventional aircraft for all the pollutants assessed except NO_x . Consequently, replacing even a relatively small number of flights may avoid a considerable quantity of taxi-related emissions, potentially explaining the substantial reductions already obtained under SOL10. Once the flights making the greatest contribution to taxi-related emissions have been replaced, the additional INDIGO flights introduced in subsequent scenarios may provide smaller incremental benefits.

NO_x represents a particular case. Although the NO_x emission rate of INDIGO aircraft during taxi is higher than that of conventional aircraft, their substantially lower emission rates during the airborne phases offset this increase, resulting in a significant reduction in the daily mean NO_x concentration. Nevertheless, the reduction in the maximum hourly average remains limited because this metric is determined by a single peak hour at each receptor. If the conventional flights responsible for this peak are not replaced, the maximum hourly concentration may remain relatively high even when the daily mean concentration decreases considerably.

Overall, the results demonstrate that the INDIGO solution could provide significant local air-quality benefits at Barcelona Airport. Nevertheless, further analysis is required to determine whether the strong initial reductions followed by relatively limited additional improvements are an inherent characteristic of Barcelona Airport or a consequence of the selected traffic sample and scenario design. Future work should therefore examine the influence of taxi distances, phase-specific emission rates, the flights selected under the replaceability and flyability rules, and their contribution to the concentration calculated at each receptor.

Pollutant	Metric	Average Reduction under SOL40 (%)
CO	max. 8h	35.75
HC	daily mean	66.44
NOX	daily mean	53.27
NOX	Max. hourly	8.99
PM	daily mean	60.07
BC	daily mean	61.14

Table 56: Result summary SOL40 relative to the reference scenario



5.2.4.2. Noise

The results for Reference and Solution 40% scenarios are presented below:

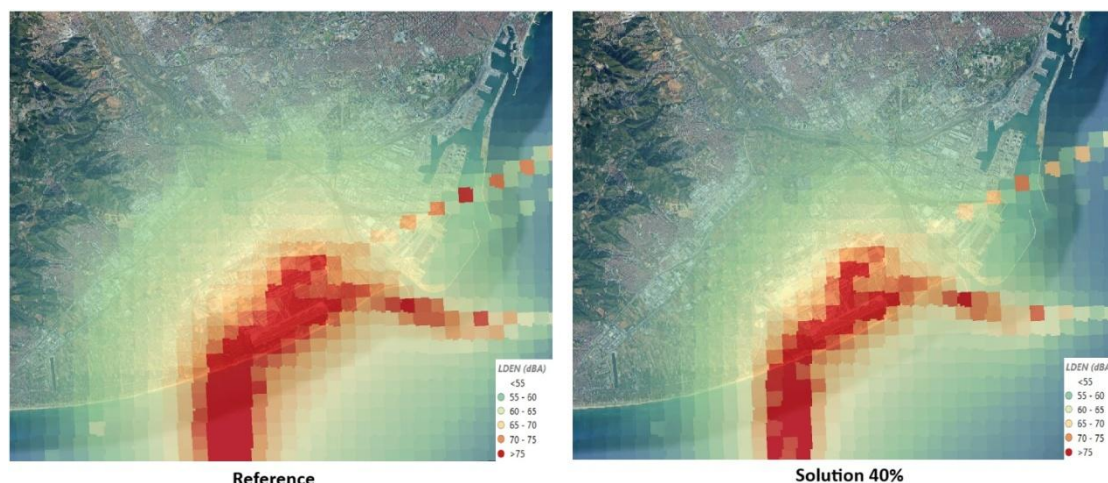


Figure 82. Comparison of LDEN results for Reference and Solution scenarios at BCN

As for the population exposed to more than 55 dB(A), the following table shows the results for each of the scenarios:

Scenario	Population exposed to more than 55 dBA (inhabitants)	Average reduction (%)
Reference	87101	-
Solution 10%	78412	10
Solution 20%	69934	20
Solution 30%	60607	30
Solution 40%	48144	45

Table 57. Population exposed in each scenario at BCN

Additionally, a spatial distribution of the population exposed is represented in the figure below:



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.



Figure 83. Comparison of population exposed before (left) and after (right) INDIGO introduction at BCN

The results for Barcelona Airport show a clear reduction in the population exposed to high levels of aircraft noise as the proposed solution increases. However, the magnitude of this reduction is more limited than in the cases analysed before (Riga, Dortmund and Madrid). This difference is largely related to the existing operational and flight-routing configuration at the airport, where aircraft are already directed towards the sea shortly after departure and before arrival, substantially limiting the exposure of densely populated areas.

In the Reference scenario, 87101 inhabitants are exposed to noise levels above 55 dBA LDEN. In contrast, in Solution 40% scenario this population decreases to 48144 inhabitants, corresponding to a 45% reduction. The intermediate solutions produce reductions of 10%, 20% and 30% for Solutions 10%, 20% and 30%, respectively, showing a progressive but comparatively moderate improvement.

The spatial distribution of the LDEN results illustrates this behaviour. In the Reference scenario, the highest noise levels are mainly concentrated along the airport and the corresponding departure and arrival corridors. Importantly, the footprint already shows a strong orientation towards the Mediterranean Sea. This means that a significant part of the potential noise impact on densely populated areas has already been avoided through the existing flight procedures.

Under Solution 40% scenario, the highest noise levels are reduced and the affected areas become narrower, particularly around the airport and the main flight paths. Nevertheless, the overall spatial configuration of the noise footprint remains relatively similar between the Reference and Solution 40% scenarios. This is consistent with the fact that the proposed measure changes the aircraft operating the flights but does not modify the existing routes or flight procedures.

The population distribution maps show the same pattern. Although the optimal solution produces a substantial reduction in the number of inhabitants exposed to levels above 55 dBA, the geographical location of the main affected areas remains broadly unchanged. The solution therefore primarily reduces the intensity of the existing noise exposure, rather than producing a major displacement or restructuring of the noise footprint.



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This behaviour contrasts with the results obtained for Riga, Dortmund and Madrid, where the introduction of INDIGO in the airports' operations has a more pronounced influence on the spatial distribution and magnitude of the affected population. In the case of Barcelona, the existing procedure of directing aircraft over the sea already provides an important reduction in exposure over the most densely populated areas. Consequently, the additional benefit achievable through aircraft replacement alone is inherently more limited, as the principal spatial noise-mitigation mechanism is already incorporated into the baseline operation.

Nevertheless, the reduction for all-day results is significant, especially in the neighbourhoods located in the surroundings and below the main flight paths (i.e. Castelldefels, Gavá, and El Prat de Llobregat).



6. Health impact

6.1. Applicable metrics and indicators

INDIGO indicators		
Area	Type	Indicator
Noise	Noise exposure (LDEN)	Population exposed to a LDEN above 45 dB(A) Population “Highly Annoyed” (%HA)
	Night-time noise (Lnight)	Population exposed to a Lnight above 40 dB(A) Population “Highly Sleep-Disturbed” (%HSD)
LAQ (emissions)	Gaseous emission (env)	Avoided population exposure associated with changes in NO _x “Number of avoided deaths”
	Particulate Matter	Avoided population exposure associated with changes in PM “Number of avoided deaths”

Table 58 INDIGO health indicators

For the LAQ assessment, number of avoided deaths are considered to present the benefits of INDIGO, since NO_x and PM are harmful pollutants for the health of the human. Thus, avoiding breathing this air, deaths are eventually avoided. For noise, the indicator is annoyance oriented, as there are no specific and mature studies that directly relate deaths with noise disturbance to humans. So, for noise, the annoyance and disturbance to number of populations avoided is presented with respect reference scenario.

6.2. Riga airport

The local air quality assessment for Riga Airport evaluates the potential health benefits associated with the progressive introduction of INDIGO aircraft into the operating fleet. Four solution scenarios are considered, corresponding to INDIGO aircraft shares of 10%, 20%, 30% and 40%. Each scenario is compared with the reference configuration, which represents airport operations performed using the conventional aircraft fleet.

The assessment follows a scenario-comparison approach. Consequently, the reported health impacts do not represent the total health burden attributable to air pollution in Riga. Instead, they quantify the incremental change in health outcomes resulting from the variation in pollutant concentrations between the reference configuration and each INDIGO scenario.

Results are estimated using BenMAP-CE by combining:

- the change in pollutant concentration relative to the reference scenario;
- the population residing within the modelled area;
- the applicable baseline mortality rate; and
- the selected concentration–response functions (CRFs).



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Results are presented separately by pollutant and health endpoint. Particular attention is given to the consistency of the estimated effect across scenarios and CRFs, as well as to the progression of the health benefit with increasing INDIGO fleet replacement.

The Solution 40% scenario represents the highest level of INDIGO aircraft introduction considered in the analysis and is therefore expected to show the largest potential improvement. Nevertheless, results for the 10%, 20% and 30% scenarios are also included to assess whether the estimated health benefit increases progressively with the level of fleet replacement. Deviations from a strictly proportional trend may occur because changes in emissions and ambient concentrations depend on the specific aircraft operations replaced under each scenario and on the spatial distribution of the affected population. Note that BC, CO and HC are not included for health and economic assessment, as specified in the methodological assumptions presented in Section 1.

6.2.1. LAQ impact on population

The estimated health impacts represent the difference in mortality between the reference and INDIGO scenarios resulting from changes in pollutant concentrations. They therefore quantify the potential health benefits associated with the introduction of INDIGO aircraft and should not be interpreted as estimates of the total mortality burden attributable to air pollution in Riga.

The assessment was performed using BenMAP-CE. The model combines the spatially resolved concentration changes with the exposed population, baseline mortality data and the selected concentration–response functions (CRFs). Mortality information was available at city level and was therefore applied consistently across the Riga districts included in the spatial analysis. This assumption ensures methodological consistency across the study area, although it does not capture potential differences in baseline mortality rates between individual districts.

The geographical scope of the health impact assessment was restricted to the administrative area of the city of Riga. Consequently, areas surrounding Riga Airport that are located outside the city boundaries, particularly to the south and west, were not included in the population-based assessment. These areas are predominantly forested and have little or no resident population and were therefore not considered relevant for the estimation of population health impacts. The results presented in this section consequently refer specifically to the population residing within the Riga study area.

6.2.1.1. Particulate matter (PM) results

The particulate matter assessment evaluates the changes in mortality associated with the differences in PM concentrations between the reference configuration and the four INDIGO solution scenarios.

Three concentration–response functions were considered in the assessment: Orellano et al. (2024), Stafoggia et al. (2022), and Anderson et al. (2022). The age range considered differs among the functions according to the population covered by the corresponding



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epidemiological studies. The Orellano et al. function covers the population aged 0–99 years, whereas the Stafoggia et al. and Anderson et al. functions are applied to the population aged 30–99 years. Consequently, the population considered in the health impact calculations differs between the functions, and the resulting estimates should be interpreted in relation to their respective age ranges.

These epidemiological functions are used to assess all-cause mortality and, where applicable, two additional cause-specific mortality endpoints: cardiovascular mortality and lung cancer mortality. The use of multiple concentration–response functions provide complementary estimates of the potential mortality benefits associated with reductions in PM exposure while accounting for differences in the epidemiological evidence and populations considered by each study.

The results should be interpreted as incremental health benefits attributable specifically to changes in airport-related PM concentrations. They do not represent the effects of eliminating total PM exposure, since the remaining conventional aircraft fleet and other urban and regional emission sources continue to contribute to population exposure.

6.2.1.1.1. All-cause mortality

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	239710	20
<i>Stafoggia et al.</i>	30–99	159311	23
<i>So and Andersen et al.</i>	30–99	159311	46

Table 59 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 10% INDIGO replacement scenario in Riga

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	239710	40
<i>Stafoggia et al.</i>	30–99	159311	45
<i>So and Andersen et al.</i>	30–99	159311	90

Table 60 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 20% INDIGO replacement scenario in Riga



Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	239710	80
<i>Stafoggia et al.</i>	30–99	159311	90
<i>So and Andersen et al.</i>	30–99	159311	181

Table 61 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 30% INDIGO replacement scenario in Riga

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	239710	83
<i>Stafoggia et al.</i>	30–99	159311	94
<i>So and Andersen et al.</i>	30–99	159311	189

Table 62 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 40% INDIGO replacement scenario in Riga

The results show a consistent reduction in all-cause mortality across all three concentration–response functions as the replacement of INDIGO aircraft increases. However, the increase in avoided deaths is not proportional to the percentage of fleet replacement. The health benefit increases substantially from the 10% to the 30% scenarios, with a particularly pronounced improvement between 20% and 30%, while the additional benefit from 30% to 40% is comparatively limited. This non-linear progression is consistent with Assumption 3 presented in Chapter 1, according to which the environmental benefits associated with increasing INDIGO fleet are not assumed to scale linearly with the percentage of aircraft replacement.

This behaviour can be explained by the different spatial patterns of concentration reduction across the solutions scenarios. In some cases, the improvement is mainly associated with a reduction in the spatial extent of the affected area, whereas in others it results from a greater reduction in concentration intensity within specific areas. Consequently, the health impact depends not only on the overall magnitude of the concentration reduction, but also on its spatial distribution relative to the exposed population. The comparatively small improvement between the 30% and 40% scenarios should therefore not be interpreted as evidence of epidemiological saturation, but rather as the result of a limited additional reduction in population-weighted PM exposure under the modelled conditions.

Differences are also observed among the concentration–response functions. So and Andersen et al. consistently produces the largest estimates of avoided deaths, while Stafoggia et al. and Orellano et al. provide lower estimates. Notably, Orellano et al. covers a



broader age range and therefore a larger population, showing that the magnitude of the estimated health impact is not determined by population size alone, but also by the epidemiological risk relationship embedded in each function. Despite these differences in magnitude, all three functions show a similar progression across the INDIGO scenarios, providing a consistent indication of the direction and overall pattern of the estimated health benefit.

Figure 84 and Figure 85 illustrate the spatial distribution of the estimated PM-related health benefits across the districts of Riga. The first one presents the results obtained using the Orellano et al. concentration–response function, selected as the primary function for the assessment, while the second shows the results obtained using the So and Andersen et al. function, which provides higher estimates of the potential health benefits.

In both figures, a graduated green scale represents the magnitude of the estimated health benefit, with darker shades corresponding to districts with a greater number of avoided premature deaths. Riga Airport, shown in brown, is located along the western boundary of the urban area and largely outside the administrative limits of the city.

The spatial distribution of the results reflects the combined influence of changes in PM concentrations and population exposure. Districts closer to airport operations may experience larger concentration reductions following the introduction of INDIGO aircraft; however, proximity to the airport alone does not determine the magnitude of the estimated health benefit. Areas with larger exposed populations may show greater benefits even when they are located farther from the airport, provided that they experience a meaningful improvement in air quality.

The assessment is restricted to the administrative area of the city of Riga and therefore excludes areas surrounding the airport that fall outside the city boundaries, particularly to the south and west. These areas are predominantly forested and have little or no resident population and were therefore not considered relevant for the population-based health impact assessment.

Overall, the maps complement the city-wide estimates by showing that the spatial allocation of health benefits is determined by the interaction between concentration reductions and the distribution of the exposed population. Consequently, the largest estimated benefits are not necessarily observed in the districts closest to the airport, but in those where improvements in air quality coincide with a sufficiently large, exposed population.



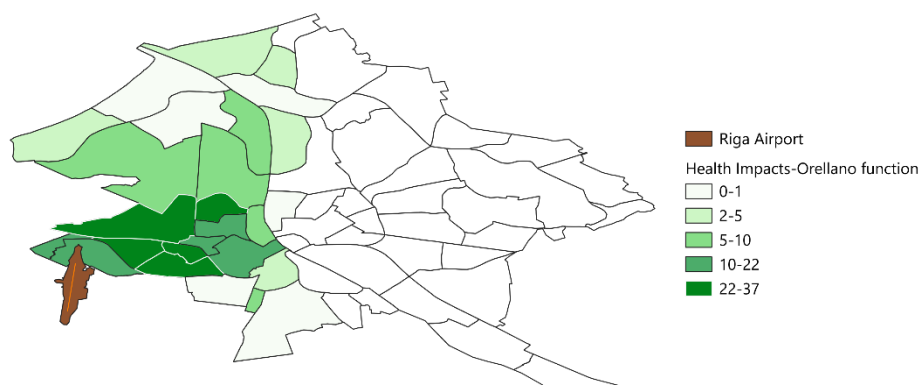


Figure 84 – Estimated avoided all-cause mortality attributable to PM reduction – Riga Airport, 40% INDIGO solution scenario (Orellano et al., 2024)

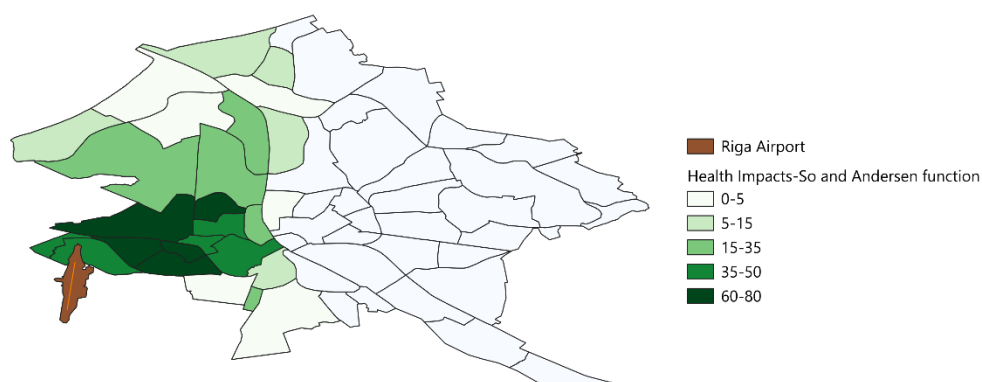


Figure 85 – Estimated avoided all-cause mortality attributable to PM reduction – Riga Airport, 40% INDIGO solution scenario (So and Andersen et al., 2022)



6.2.1.1.2. Lung cancer mortality

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	239710	< 1
<i>So and Andersen et al.</i>	30–99	159311	1

Table 63 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 10% INDIGO replacement scenario in Riga

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	239710	1
<i>So and Andersen et al.</i>	30–99	159311	3

Table 64 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 20% INDIGO replacement scenario in Riga

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	239710	1
<i>So and Andersen et al.</i>	30–99	159311	5

Table 65 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 30% INDIGO replacement scenario in Riga

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	239710	2
<i>So and andersen et al.</i>	30–99	159311	6

Table 66 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 40% INDIGO replacement scenario in Riga

The lung cancer mortality results show a consistent improvement as the introduction of INDIGO aircraft increases. Although the absolute number of avoided deaths remains limited compared with the all-cause mortality results, both concentration–response functions indicate a progressive health benefit associated with the reduction in PM exposure.

The magnitude of the estimated effect differs considerably between the two epidemiological functions. So and Andersen et al. consistently produces higher estimates than Orellano et al.,



despite being applied to a smaller population restricted to the 30–99 age range. This confirms that differences in the estimated health impact are primarily driven by the epidemiological risk relationship embedded in each concentration–response function rather than by the size of the population considered alone. Orellano et al. provides a more conservative estimate, with the health benefit remaining very limited at lower INDIGO introduction levels and becoming more evident as the replacement rate increases.

Unlike the pattern observed for all-cause mortality, the lung cancer results continue to increase between the 30% and 40% scenarios, although the incremental improvement remains relatively small. Overall, the results indicate that the progressive introduction of INDIGO aircraft can contribute to reducing PM-related lung cancer mortality, but the magnitude of this specific health benefit is substantially smaller than that estimated for all-cause mortality. Given the small absolute number of avoided deaths, particularly under the lower-solution scenarios, these results should be interpreted cautiously and primarily in terms of their overall trend rather than small differences between individual scenarios.

6.2.1.1.3. Cardiovascular mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	So and Andersen et al.	30–99	159311	21
20%	So and Andersen et al.	30–99	159311	42
30%	So and Andersen et al.	30–99	159311	85
40%	So and Andersen et al.	30–99	159311	88

Table 67 – Estimated avoided cardiovascular mortality associated with changes in PM concentrations under the INDIGO solution scenarios in Riga

The cardiovascular mortality results show a clear increase in avoided deaths as the introduction of INDIGO aircraft rises, with the largest improvements occurring up to the 30% scenario and a more limited additional benefit at 40%.

The resulting health benefit is further influenced by the magnitude and spatial distribution of the concentration reductions and by the population exposed within the affected districts. Therefore, differences between consecutive scenarios depend both on which conventional aircraft are replaced and on how the resulting emission reductions translate into changes in population exposure.

Overall, the results confirm that the cardiovascular health benefits do not scale proportionally with INDIGO fleet solution. The limited incremental benefit at the highest solution level should not be interpreted as epidemiological saturation, but as a consequence of the fleet composition and the resulting concentration and exposure patterns under the modelled scenarios.



6.2.1.2. Nitrogen oxides (NO_x) results

6.2.1.2.1. All-cause mortality

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	239710	13
<i>Stafoggia et al.</i>	30–99	159311	11

Table 68– Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 10% INDIGO scenario in Riga

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	239710	40
<i>Stafoggia et al.</i>	30–99	159311	35

Table 69 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 20% INDIGO scenario in Riga

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	239710	43
<i>Stafoggia et al.</i>	30–99	159311	38

Table 70– Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 30% INDIGO scenario in Riga

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	239710	45
<i>Stafoggia et al. (2022)</i>	30–99	159311	39

Table 71 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 40% INDIGO scenario in Riga

The NO_x-related all-cause mortality results show a clear health benefit associated with the progressive introduction of INDIGO aircraft. Both concentration–response functions indicate a marked improvement between the 10% and 20% solution scenarios, followed by smaller incremental benefits at higher replacement levels.

This non-linear response indicates that the percentage of aircraft replaced does not translate directly into an equivalent reduction in population exposure. Under the modelled conditions, a substantial share of the reduction in population-weighted NO_x exposure is already



achieved at 20% solution, leaving comparatively smaller additional improvements for the subsequent scenarios. As for PM, this behaviour reflects the combined influence of fleet-replacement characteristics, changes in pollutant concentrations and their spatial relationship with the exposed population.

Kasdagli et al. consistently estimates a slightly higher number of avoided deaths than Stafoggia et al., despite differences in the age range and population considered. Nevertheless, both functions show a similar evolution across the scenarios, indicating that the overall pattern is primarily associated with the underlying NO_x concentration and exposure changes rather than with the choice of concentration–response function. The limited incremental benefit at higher replacement levels should therefore not be interpreted as epidemiological saturation.

Figure 86 – Estimated avoided all-cause mortality attributable to NO_x reduction – Riga Airport, 40% INDIGO replacement scenario (Orellano et al., 2024) and Figure 87 illustrate the spatial distribution of NO_x-related health benefits under the 40% INDIGO solution scenario using the Stafoggia et al. and Kasdagli et al. concentration–response functions, respectively. The spatial pattern is broadly consistent with that observed for PM and reflects the interaction between changes in NO_x concentrations and the distribution of the exposed population.

Although districts closer to Riga Airport may experience more direct effects from changes in airport-related emissions, proximity alone does not determine the magnitude of the estimated health benefit. Riga Airport is located along the western boundary of the urban area and largely outside the administrative limits of the city, while some of the adjacent districts have relatively small populations. Consequently, larger health benefits may occur in more densely populated districts where relevant reductions in NO_x concentrations coincide with greater population exposure.

Overall, the spatial analysis complements the city-wide results by showing that the distribution of NO_x-related health benefits is determined by where concentration reductions occur relative to the exposed population, rather than by distance from the airport alone.



Figure 86 – Estimated avoided all-cause mortality attributable to NO_x reduction – Riga Airport, 40% INDIGO replacement scenario (Orellano et al., 2024)



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Figure 87 – Estimated avoided all-cause mortality attributable to NO_x reduction – Riga Airport, 40% INDIGO replacement scenario (Stafoggia et al., 2022)

6.2.1.2.2. Respiratory mortality

Solution	Study	Age range	Population considered	Estimated avoid deaths
10%	<i>Kasdagli et al.</i>	0–99 years	239710	<1
20%	<i>Kasdagli et al.</i>	0–99 years	239710	1
30%	<i>Kasdagli et al.</i>	0–99 years	239710	1
40%	<i>Kasdagli et al.</i>	0–99 years	239710	2

Table 72 – Estimated avoided respiratory mortality associated with changes in NO_x concentrations

The respiratory mortality results indicate a positive but limited health benefit associated with the reduction in NO_x concentrations. The estimated number of avoided deaths increases progressively with INDIGO introduction, although the absolute magnitude of the effect remains small across all scenarios.

Given the low number of estimated avoided deaths, particularly at the lower replacement levels, differences between individual scenarios should be interpreted cautiously. The results are more informative in terms of their overall direction than in terms of the numerical difference between consecutive scenarios. Nevertheless, the consistent progression indicates that increasing INDIGO replacement is associated with a reduction in NO_x-related respiratory mortality, with the largest estimated benefit obtained under the 40% scenario.

Compared with the all-cause and cardiovascular mortality results, the respiratory endpoint represents a substantially smaller component of the overall estimated NO_x-related health benefit. This difference reflects the endpoint-specific concentration–response relationship



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applied in the Kasdagli et al. function and should not be interpreted as an absence of benefit, but rather as a more limited estimated effect for this specific cause of mortality.

6.2.1.2.3. Cardiovascular mortality

Solution	Concentration–response function	Age range	Population considered	Estimated avoid deaths
10%	<i>Kasdagli et al.</i>	0–99	239710	7
20%	<i>Kasdagli et al.</i>	0–99	239710	22
30%	<i>Kasdagli et al.</i>	0–99	239710	24
40%	<i>Kasdagli et al.</i>	0–99	239710	25

Table 73 – Estimated avoided cardiovascular mortality associated with changes in NOx concentrations

The cardiovascular mortality results show a considerably larger health benefit than that estimated for respiratory mortality. A pronounced increase in avoided deaths is observed between the 10% and 20% INDIGO solution scenarios, whereas the additional improvement becomes substantially smaller at higher replacement levels.

As discussed for the other NOx mortality endpoints, this flattening should not be interpreted as epidemiological saturation. Rather, it reflects the underlying relationship between fleet replacement, spatial changes in NOx concentrations and population exposure. Under the modelled conditions, increasing INDIGO introduction beyond 20% continues to reduce the estimated cardiovascular mortality burden, but the additional reduction in population-weighted exposure is comparatively limited. Consequently, the health benefit continues to increase, although at a substantially lower rate at the highest replacement levels.

6.2.1.3. Overall assessment

To summarise the potential health benefits associated with the highest level of INDIGO implementation, the results obtained under the 40% solution scenario were considered. For each pollutant, the table below presents the minimum–maximum range of estimated avoided all-cause deaths across the concentration–response functions applied. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals. The estimates are presented separately by pollutant and should not be added together.

Pollutant	Concentration–response functions considered	Estimated range of avoided deaths
PM	Orellano et al.; Stafoggia et al.; So and Andersen et al.	83-189
NOx	Kasdagli et al.; Stafoggia et al.	39-45

Table 74 – Summary of estimated avoided deaths by pollutant for Riga Airport under the 40% INDIGO solution scenario



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6.2.2. Noise impact on population

Following the proposed methodology from WHO's guidelines (see section 3.6.1.7.) and applying them to Riga's airport, the noise impact on population assessment has been carried out, in first place, by detecting the zones where population is exposed either to a LDEN above 45 dB (A) or to a Lnight above 40 dB (A).

Scenario	Population exposed to more than 45 dBA LDEN (inhabitants)	Average reduction (%)
Reference	123840	-
Solution 10%	103880	16
Solution 20%	98130	21
Solution 30%	88195	29
Solution 40%	77465	37

Table 75. Population above 45 dBA LDEN at RIX

The results show a progressive reduction in the population affected by aircraft noise as the number of aircraft replaced by INDIGO increases.

Scenario	Population exposed to more than 40 dBA Lnight (inhabitants)	Average reduction (%)
Reference	71305	-
Solution 10%	61950	13
Solution 20%	59875	16
Solution 30%	49975	30
Solution 40%	43780	39

Table 76. Population above 40 dBA Lnight at RIX

At night, same trend as LDEN values is observed. The overall reduction is slightly higher than the all-day results, due to the fact that most of the airport operations take place during the daytime.

As for the annoyance on population:



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Scenario	Population annoyed (inhabitants)	Average reduction (%)
Reference	16256	-
Solution 10%	13814	15
Solution 20%	12658	22
Solution 30%	10833	33
Solution 40%	9496	42

Table 77. Population annoyed at RIX

The population considered annoyed by aircraft noise shows an even greater reduction, from 16256 to 9496 inhabitants, equivalent to 42%.

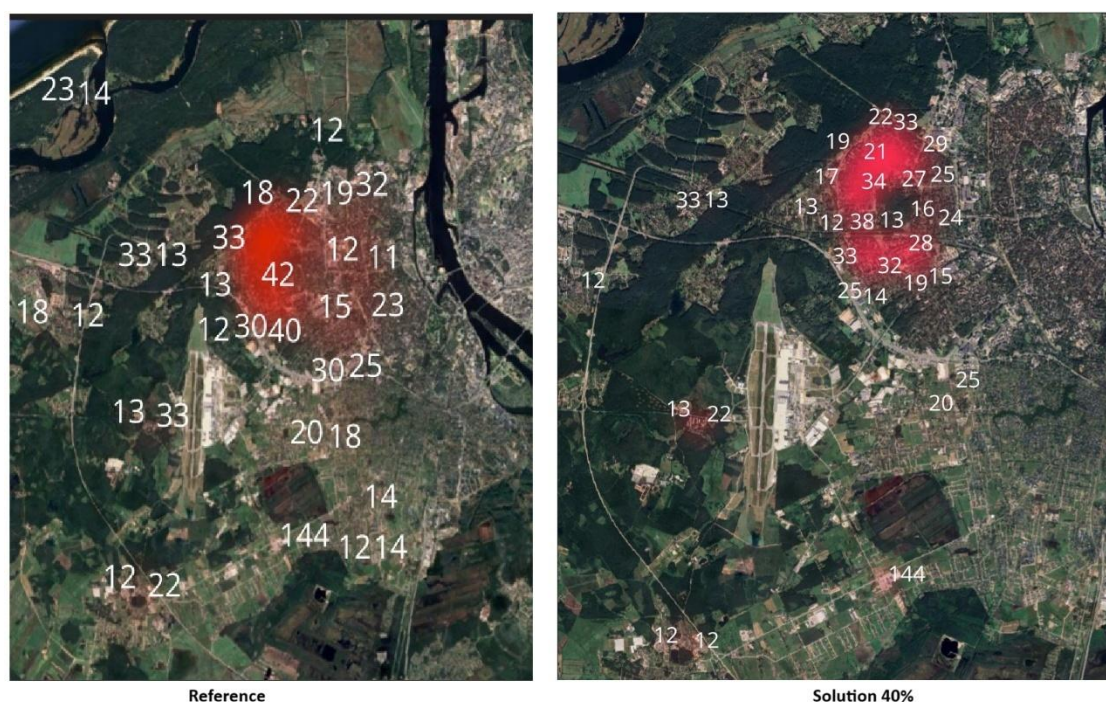


Figure 88. Spatial distribution of annoyed population both in Reference and Solution scenarios at RIX

The spatial distribution shown in the maps is consistent with these overall figures. In the Reference scenario, the affected population is more concentrated around the main areas influenced by the airport and its flight paths, with several locations showing relatively high values. Under Solution 40% scenario, the areas with the highest concentrations of affected population become clearly less extensive and less intense, although some localised areas of residual impact remain.

The table below shows the results on sleep disturbance:



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Scenario	Population affected by sleep disturbance (inhabitants)	Average reduction (%)
Reference	8283	-
Solution 10%	7187	13
Solution 20%	6949	16
Solution 30%	5794	30
Solution 40%	5059	39

Table 78. HSD at RIX

The figure below shows the spatial hotspots regarding sleep disturbance:

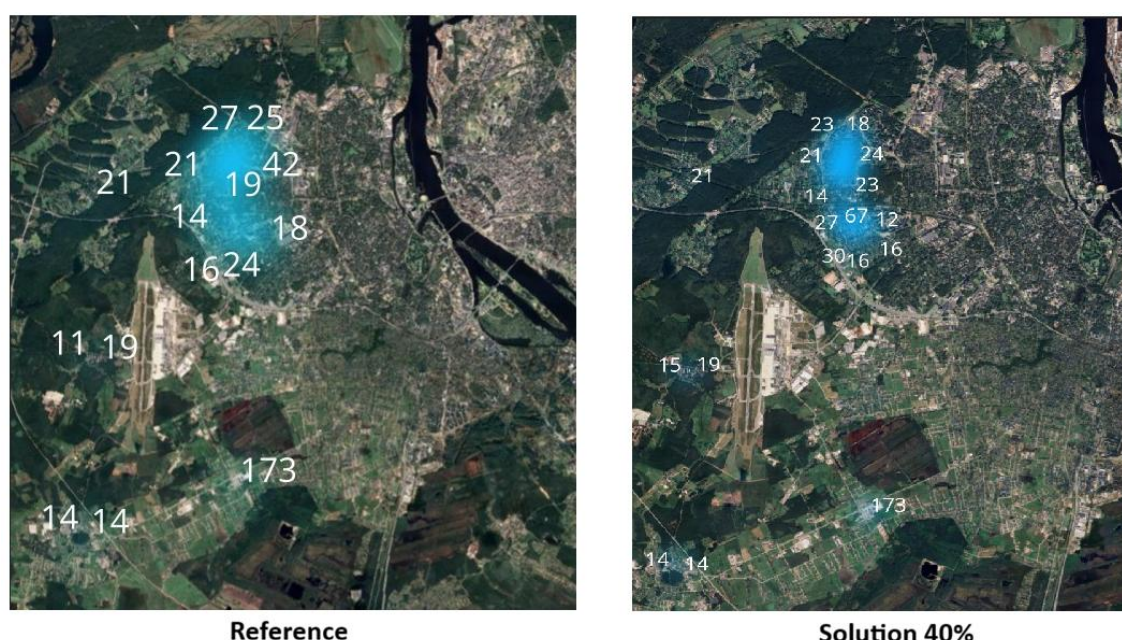


Figure 89. Spatial distribution of sleep disturbance on population both in Reference and Solution scenarios at RIX

The differences observed between daytime and night-time indicators should also be considered in the context of the different operational patterns of the airport. Aircraft activity is generally greater during the daytime than during the night, meaning that the overall contribution of airport operations to population exposure is more pronounced during the daytime period. Consequently, the absolute population affected by the daytime-related indicators is higher. At night, the lower number of aircraft operations results in a lower baseline exposure, but changes in the noise scenario can produce a more noticeable relative reduction in the population exposed to night-time noise and potentially affected in terms of sleep disturbance.

Overall, the results indicate that Solution 40% scenario (highest INDIGO replacement) produces a substantial reduction in both the number of inhabitants affected and the spatial



extent of the main areas of noise impact. The reduction is particularly relevant for annoyance and night-time exposure, this can therefore be expected to provide benefits for the affected population, potentially contributing to improved living conditions and quality of life in the areas surrounding the airport.

In particular, the reduction in night-time exposure may contribute to more favorable conditions for rest and sleep, while the overall reduction in noise-related annoyance may improve the acoustic environment experienced by local people at RIX. In addition, a reduction in aircraft noise exposure may have a positive effect on the attractiveness of the surrounding residential areas and, consequently, may contribute to maintaining or increasing residential property values.

6.3. Dortmund airport

6.3.1. LAQ impact on population

Following the assessment conducted for Riga, the same methodological framework was applied to the Dortmund case study to evaluate the potential health benefits associated with the progressive introduction of INDIGO aircraft. The analysis considers the population of the city of Dortmund and compares the four INDIGO solution scenarios (10%, 20%, 30% and 40%) with the corresponding reference configuration based exclusively on conventional aircraft.

As in the Riga case study, the resulting estimates represent changes in mortality associated with the differences in pollutant concentrations between the reference and INDIGO scenarios.

For the spatial assessment, the city of Dortmund was divided into 12 districts. Baseline mortality information was available at city level and was therefore applied uniformly across these districts. Consequently, differences in the spatial distribution of the estimated health benefits are primarily determined by the modelled pollutant reductions and the distribution of the exposed population, while potential district-level variations in baseline mortality are not captured.

The comparison across the four replacement levels allows the evolution of the health benefits to be assessed as conventional aircraft are progressively replaced by INDIGO aircraft. As discussed for Riga and according to the fleet-replacement assumptions defined in Chapter 1, these benefits are not expected to increase proportionally with the percentage of INDIGO replacement, since the emission characteristics of the aircraft replaced differ between scenarios.



6.3.1.1. Particulate matter (PM) results

6.3.1.1.1. All-cause mortality

Concentration–response function	Age range (years)	Population considered¹	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	<1
<i>Stafoggia et al.</i>	30–99	197023	2
<i>So and Andersen et al.</i>	30–99	197023	1

Table 79 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 10% INDIGO solution scenario in Dortmund

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	2
<i>So and Andersen et al.</i>	30–99	197023	6
<i>Stafoggia et al.</i>	30–99	197023	3

Table 80 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 20% INDIGO solution scenario in Dortmund

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	4
<i>So and andersen et al.</i>	30–99	197023	9
<i>Stafoggia et al.</i>	30–99	197023	4

Table 81 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 30% INDIGO solution scenario in Dortmund

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	4
<i>So and andersen et al.</i>	30–99	197023	10
<i>Stafoggia et al.</i>	30–99	197023	5

Table 82 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 40% INDIGO solution scenario in Dortmund

The PM-related all-cause mortality results indicate an overall increase in health benefits as the introduction of INDIGO aircraft increases. All three concentration–response functions show a consistent progression across the scenarios, although the magnitude of the estimated effect differs among them. The increase is not proportional to the percentage of fleet replacement, with larger improvements at intermediate replacement levels and a more limited incremental benefit between SOL30 and SOL40. This behaviour is consistent with the



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fleet-replacement assumptions adopted in the assessment, according to which changes in emissions and resulting PM concentrations do not necessarily scale linearly with INDIGO fleet solution.

The magnitude of the estimated benefits remains relatively limited compared with the larger airport case studies. This result should be interpreted in the context of the Dortmund case study, particularly the size and spatial distribution of the exposed population and the concentration changes generated by the modelled scenarios. The relatively low number of avoided deaths therefore reflects the specific exposure conditions considered in the assessment and should not, by itself, be interpreted as evidence of a negligible effect of the INDIGO solution.

Differences are also observed among the concentration–response functions, reflecting both their underlying epidemiological risk relationships and the population groups to which they are applied. Orellano et al. considers the population aged 0–99 years, whereas Stafoggia et al. and So and Andersen et al. are applied to the population aged 30–99 years. The resulting estimates should therefore be interpreted as alternative estimates based on different epidemiological assumptions rather than as directly comparable measures of the same effect. Despite these differences in magnitude, the functions show a consistent scenario-dependent pattern, supporting the overall direction of the estimated health benefit.

To better understand the spatial distribution of the estimated health effects across the city, two maps of Dortmund are presented in Figure 90 and Figure 91. The maps show the administrative districts considered in the analysis and highlight the location of Dortmund Airport. This spatial representation provides the geographical context needed to interpret the distribution of the estimated health benefits, particularly in relation to the proximity to the airport and the population exposed within each district.

The first figure shows the results obtained using Orellano et al. (2024), selected as the principal function, while the second one presents the results obtained using So and Andersen et al. (2022), which generated the highest overall estimate among the functions considered.



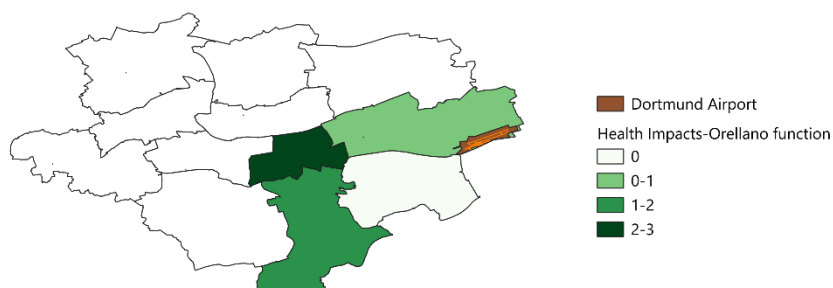


Figure 90 – Estimated avoided all-cause mortality attributable to PM reduction – Dortmund Airport, 40% INDIGO solution scenario (Orellano et al., 2024)

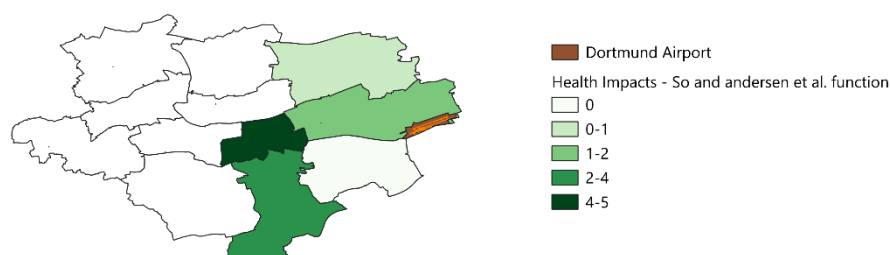


Figure 91 – Estimated avoided all-cause mortality attributable to PM reduction – Dortmund Airport, 40% INDIGO solution scenario (So and Andersen et al., 2024)

Both maps show a comparable geographical pattern. The estimated benefits are concentrated in a limited number of districts located mainly in the central, eastern and southern parts of the study area. By contrast, several districts in the western and north-western portions of the modelled area show no measurable avoided mortality or values below the lowest map classification.

As also observed in the Riga study, the largest benefit is not necessarily found in the district immediately surrounding Dortmund Airport. This is an expected result because the number of avoided deaths in a district depends on several interacting factors:

- the magnitude of the local reduction in PM concentration;
- the number of inhabitants exposed to the reduction;



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- the age structure of the exposed population;
- the baseline mortality rate applied to the population; and
- the concentration–response coefficient used in the calculation.

Although the So and Andersen et al. function produces higher absolute estimates than Orellano et al., the main areas of positive impact remain broadly consistent between the two functions. This indicates that the overall spatial pattern is relatively stable across the epidemiological functions, while the magnitude of the estimated benefit remains sensitive to the selected concentration–response relationship.

Overall, the maps show that PM-related health benefits are not confined to the immediate surroundings of Dortmund Airport, but reflect the spatial interaction between changes in pollutant concentrations and the characteristics of the exposed population.

6.3.1.1.2. Lung cancer mortality

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	<1
<i>So and Andersen et al.</i>	30–99	197023	<1

Table 83 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 10% INDIGO solution scenario in Dortmund

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	<1
<i>So and Andersen et al.</i>	30–99	197023	<1

Table 84 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 20% INDIGO solution scenario in Dortmund

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Orellano et al.</i>	0–99	275245	1
<i>So and Andersen et al.</i>	30–99	197023	3

Table 85 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 30% INDIGO solution scenario in Dortmund



<i>Concentration–response function</i>	<i>Age range (years)</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	275245	1
<i>So and Andersen et al.</i>	30–99	197023	3

Table 86 – Estimated avoided lung cancer mortality associated with changes in PM concentrations under the 40% INDIGO solution scenario in Dortmund

The results for lung cancer mortality show a limited but positive health benefit associated with the progressive introduction of INDIGO aircraft. At the lower replacement levels, the estimated effect remains below one avoided death for both concentration–response functions, reflecting the relatively small changes in PM exposure combined with the limited scale of the Dortmund case study.

A clearer benefit emerges at higher replacement levels, particularly from Solution 30 onwards. However, the estimates remain essentially unchanged between Solutions 30 and 40, indicating that the additional fleet replacement in the highest-replacement scenario produces only a limited further reduction in the PM exposure relevant to this endpoint. As discussed previously, this behaviour is consistent with the fleet-replacement assumptions adopted in the analysis, according to which increases in INDIGO introduction do not necessarily result in proportional emission and concentration reductions.

Overall, the estimated lung cancer mortality benefits are smaller than those obtained for all-cause mortality, as expected for a cause-specific endpoint.

6.3.1.1.3. Cardiovascular mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al	275245	<1
20%	Kasdagli et al	275245	<1
30%	Kasdagli et al	275245	2
40%	Kasdagli et al	275245	3

Table 87 – Estimated avoided cardiovascular deaths across INDIGO scenarios — Kasdagli et al

The cardiovascular mortality results show an increase in the estimated health benefit with increasing INDIGO fleet introduction. The estimated avoided mortality remains below one case in the lower-replacement scenarios and becomes more evident at higher replacement levels, with the largest benefit observed under the 40% solution scenario.



These results provide an endpoint-specific perspective on the PM-related mortality benefits and should be interpreted alongside the all-cause mortality assessment. Cardiovascular mortality represents a component of all-cause mortality and should therefore not be added to the all-cause estimates when reporting the overall mortality benefit.

6.3.1.2. Nitrogen oxides (NOx) results

6.3.1.2.1. All-cause mortality

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	275245	6
<i>Stafoggia et al.</i>	30–99	197023	5

Table 88 – Estimated gross avoided all-cause mortality associated with NOx concentration changes under the 10% INDIGO scenario in Dortmund

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	275245	9
<i>Stafoggia et al.</i>	30–99	197023	8

Table 89 – Estimated gross avoided all-cause mortality associated with NOx concentration changes under the 20% INDIGO scenario in Dortmund

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	275245	10
<i>Stafoggia et al.</i>	30–99	197023	9

Table 90 – Estimated gross avoided all-cause mortality associated with NOx concentration changes under the 30% INDIGO scenario in Dortmund

Concentration–response function	Age range (years)	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	275245	11
<i>Stafoggia et al.</i>	30–99	197023	10

Table 91 – Estimated gross avoided all-cause mortality associated with NOx concentration changes under the 40% INDIGO scenario in Dortmund



The NO_x-related all-cause mortality results show a consistent increase in avoided deaths as INDIGO fleet introduction rises. The largest incremental improvement occurs at the lower replacement levels, followed by more limited gains towards SOL40, confirming the non-linear relationship between fleet replacement and the resulting health benefit already observed for PM.

The two concentration–response functions provide closely aligned estimates, with Kasdagli et al. producing slightly higher values than Stafoggia et al. Despite differences in the age ranges and populations considered, both functions show a similar progression across the scenarios, indicating a consistent overall pattern of NO_x-related health benefits.

Overall, the results indicate a positive but moderate reduction in NO_x-related mortality across the Dortmund study area, with the magnitude of the estimated benefit reflecting the specific concentration and population-exposure patterns generated under the modelled scenarios.

The figures below present the spatial distribution of the estimated health benefits across the Dortmund study area, highlighting the geographical variation in avoided mortality among the districts considered in the assessment.

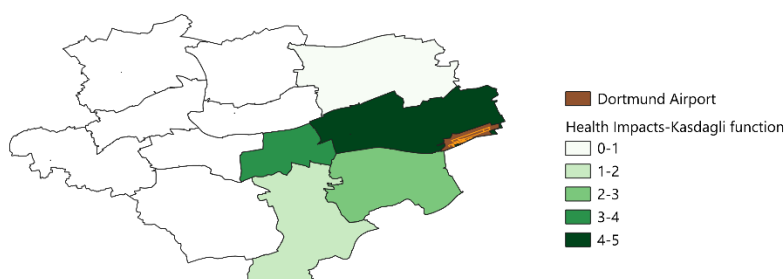


Figure 92 – Estimated avoided all-cause mortality attributable to NO_x reduction – Dortmund Airport, 40% INDIGO solution scenario (Orellano et al., 2024)



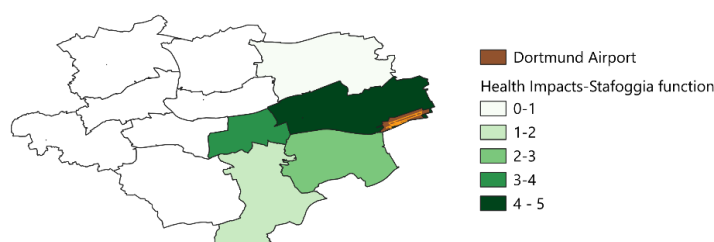


Figure 93 – Estimated avoided all-cause mortality attributable to NO_x reduction – Dortmund Airport, 40% INDIGO solution scenario (Stafoggia et al., 2022)

They show a consistent pattern across the Kasdagli and Stafoggia concentration–response functions. In both cases, the largest benefits are concentrated in the eastern districts of Dortmund, while comparatively limited impacts are observed across the western part of the city. Although some differences in magnitude are visible between the two functions, the overall spatial pattern remains similar. This indicates that the geographical distribution of the health benefits is primarily driven by the combined effect of changes in pollutant concentrations and population exposure, rather than by proximity to Dortmund Airport alone.

6.3.1.2.2. Respiratory mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range (years)</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al	0–99	275245	<1
20%	Kasdagli et al	0–99	275245	1
30%	Kasdagli et al	0–99	275245	1
40%	Kasdagli et al	0–99	275245	1

Table 92 – Estimated avoided respiratory deaths across INDIGO scenarios — Kasdagli et al

The respiratory mortality results indicate a small positive health benefit associated with the reduction in NO_x concentrations. The estimated effect remains below one avoided death in SOL10 and reaches approximately one avoided death from SOL20 onwards. No further increase is visible in the rounded estimates for SOL30 and SOL40, indicating that the additional changes in NO_x exposure at higher INDIGO replacement levels are not sufficient to produce a substantial increase in this cause-specific mortality endpoint.

This limited magnitude is consistent with the narrower nature of respiratory mortality compared with all-cause mortality and with the characteristics of the Dortmund case study, where both the exposed population and airport traffic are relatively limited compared with the larger airports analysed. Moreover, the apparent stability between SOL20 and SOL40



should not necessarily be interpreted as an absence of additional benefit, since small differences between scenarios may be masked when the results are expressed as rounded numbers of avoided deaths.

Overall, the results suggest that the introduction of INDIGO aircraft provides a modest respiratory health benefit in Dortmund, with most of the measurable improvement already achieved at the lower-to-intermediate replacement levels.

6.3.1.2.3. Cardiovascular mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al	0–99	275245	2
20%	Kasdagli et al	0–99	275245	3
30%	Kasdagli et al	0–99	275245	3
40%	Kasdagli et al	0–99	275245	4

Table 93 – Estimated avoided cardiovascular deaths across INDIGO scenarios — Kasdagli et al

The cardiovascular mortality results show an overall increase in avoided deaths with increasing INDIGO fleet introduction, although the progression is not linear. The estimated benefit remains relatively stable between the 20% and 30% solution scenarios before reaching its highest value under the 40% configuration.

Compared with respiratory mortality, the cardiovascular endpoint shows a more pronounced estimated benefit under the Kasdagli et al. concentration–response function. Nevertheless, the absolute magnitude remains relatively limited within the Dortmund study area.

Overall, the results indicate a modest cardiovascular health benefit associated with the progressive introduction of INDIGO aircraft, consistent with the general positive trend observed for NO_x-related mortality.

6.3.1.3. Overall assessment

The table below summarises the estimated health benefits under the 40% INDIGO solution scenario. For each pollutant, the minimum–maximum range of avoided all-cause deaths is presented across the concentration–response functions considered. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals. The NO_x-related estimates show a narrower range than those for PM, indicating closer agreement between the selected functions. The results represent separate estimates of mortality benefits and should not be added together.



Pollutant	Concentration–response functions considered	Estimated range of avoided deaths
PM	Orellano et al.; Stafoggia et al.	4-10
NO _x	Kasdagli et al.; Stafoggia et al.	10-11

Table 94 – Summary of estimated avoided deaths by pollutant for Dortmund Airport under the 40% INDIGO solution scenario

6.3.2. Noise impact on population

Following the proposed methodology from WHO's guidelines (see section 3.6.1.7.) and applying them to Dortmund's airport, the noise impact on population assessment has been carried out, in first place, by detecting the zones where population is exposed either to a LDEN above 45 dB (A) or to a Lnight above 40 dB (A).

Scenario	Population exposed to more than 45 dBA LDEN (inhabitants)	Average reduction (%)
Reference	20763	-
Solution 10%	17902	14
Solution 20%	16012	23
Solution 30%	15040	28
Solution 40%	13595	35

Table 95. Population above 45 dBA LDEN at DTM

The results show a progressive reduction in the population affected by aircraft noise as the number of aircraft replaced by INDIGO increases.

Scenario	Population exposed to more than 40 dBA Lnight (inhabitants)	Average reduction (%)
Reference	8813	-
Solution 10%	6527	25
Solution 20%	4451	50
Solution 30%	3956	55
Solution 40%	3451	61

Table 96. Population above 40 dBA Lnight at DTM



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Scenario	Population affected by sleep disturbance (inhabitants)	Average reduction (%)
Reference	2039	-
Solution 10%	926	55
Solution 20%	637	69
Solution 30%	561	72
Solution 40%	537	74

Table 98. HSD at DTM

The figure below shows the spatial hotspots regarding sleep disturbance:

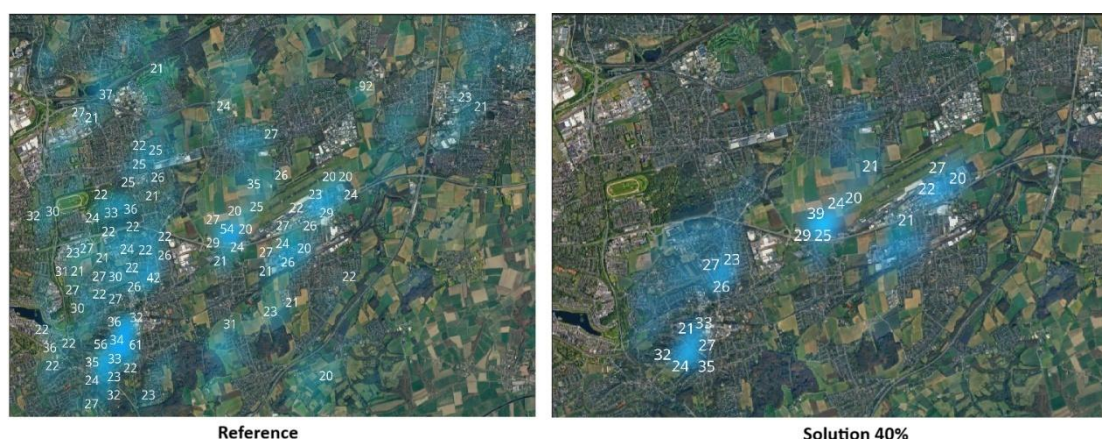


Figure 95. Spatial distribution of sleep disturbance on population both in Reference and Solution scenarios at DTM

The results for annoyance and sleep disturbance (HSD) at Dortmund Airport show a particularly strong reduction under the proposed solutions, especially for night-time impacts. This behaviour is closely related to the very limited amount of scheduled aircraft activity during the night at the airport. Dortmund Airport operates under a night-time restriction, with regular operations concentrated during the daytime and only a limited number of late-evening operations and specific exceptions outside the regular operating period.

For annoyance, the estimated affected population decreases from 4750 inhabitants in the Reference scenario to 2207 when a 40% of INDIGO aircraft are replaced, corresponding to a 54% reduction. The reduction is already substantial for Solution 10%, reaching 34%, and increases progressively to 44% for Solution 20% and 48% for Solution 30%. This demonstrates that the replacement of aircraft by INDIGO aircraft has a significant effect on the population experiencing noise annoyance, despite the relatively low and spatially dispersed population around the airport.



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The effect is even more pronounced for sleep disturbance. The population highly disturbed decreases from 2039 inhabitants in the Reference scenario to only 537 under Solution 40%, corresponding to a 74% reduction. The first solution (10%) already reduces the affected population by 55%, while Solutions 20% and 30% achieve reductions of 69% and 72%, respectively.

This particularly strong reduction in HSD indicator can be explained by the very limited number of aircraft movements during the night. Since there are considerably fewer night-time operations than day-time operations, the population potentially exposed to night-time aircraft noise is substantially lower. The remaining night-time noise footprint is therefore more closely associated with the immediate surroundings of the airport, rather than extending continuously along the main flight paths.

This behaviour can be clearly observed in the spatial distribution maps. In the LDEN results, the affected population remains distributed by following the main arrival and departure trajectories. The Reference scenario shows a few population concentrations distributed along these corridors, and although Solution 40% substantially reduces their magnitude, the overall spatial pattern of the exposure remains related to the aircraft trajectories.

In contrast, the maps derived from Lnight show a more compact pattern. In the Reference scenario, sleep disturbance is distributed across several relatively small population concentrations, but the affected area is already considerably more limited than for LDEN. In Solution 40%, most of these concentrations are strongly reduced or disappear, leaving the main areas of residual sleep disturbance closer to the airport itself.

This difference is particularly important when interpreting the results. The limited number of night-time aircraft movements means that there is less opportunity for aircraft noise to generate a widespread night-time exposure footprint. Consequently, replacing the remaining aircraft with INDIGO produces a comparatively large reduction in the population affected by sleep disturbance. The 74% reduction in HSD is therefore consistent with the specific operational characteristics of Dortmund and should not be interpreted in the same way as the results for airports with substantial night-time traffic.

From a health perspective, this is particularly relevant because night-time aircraft noise is associated with sleep disturbance, and the WHO identifies 40 dBA Lnight as the recommended guideline level for aircraft noise. The substantial reduction in both the population above this threshold and the estimated population affected by sleep disturbance therefore indicates a potentially important improvement in night-time acoustic conditions.

6.4. Madrid airport

The assessment for Madrid followed the same methodology applied to the other airport case studies. However, the concentration–response function from So and Andersen et al. was excluded because compatible baseline mortality data were not available for the population subgroup required by the function.



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Consequently, PM-related cardiovascular mortality could not be quantified for Madrid within the present assessment, as this endpoint was represented exclusively by the excluded function among the selected CRFs. This limitation reflects a gap in data compatibility and should not be interpreted as an absence of potential cardiovascular benefits associated with reduced PM exposure.

6.4.1. LAQ impact on population

6.4.1.1. Particulate matter (PM) results

6.4.1.1.1. All-cause mortality

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	1465590	33
<i>Stafoggia et al.</i>	30–99	1019268	37

Table 99 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 10% INDIGO solution scenario

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	1465590	49
<i>Stafoggia et al.</i>	30–99	1019268	54

Table 100 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 20% INDIGO solution scenario

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	1465590	76
<i>Stafoggia et al.</i>	30–99	1019268	83

Table 101 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 30% INDIGO solution scenario



<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	1465590	86
<i>Stafoggia et al.</i>	30–99	1019268	94

Table 102 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 40% INDIGO solution scenario

The PM-related all-cause mortality results show a clear increase in health benefits as INDIGO fleet introduction rises. Both concentration–response functions indicate a substantial improvement up to the 30% solution scenario, followed by a more moderate additional benefit at Solution 40%. This non-linear progression is consistent with the fleet-replacement assumptions defined in Chapter 1 and with the trends observed in the other airport case studies.

Stafoggia et al. consistently produces slightly higher estimates than Orellano et al., despite being applied to the smaller population aged 30–99 years. This difference reflects the distinct epidemiological relationships underlying the two functions rather than population size alone. Overall, the results indicate a substantial PM-related health benefit for Madrid, with the larger absolute number of avoided deaths also reflecting the considerably larger exposed population included in this case study.

Figure 96 and Figure 97 compare the spatial distribution of the estimated PM-related all-cause mortality benefits across Madrid districts under the INDIGO scenario, using the concentration–response functions from Orellano et al. and Stafoggia et al., respectively. In both cases, the health benefits show a clear spatial heterogeneity, with the largest effects concentrated in the eastern and north-eastern sectors of the city, in the districts surrounding the airport area. Conversely, most western and central districts show comparatively limited benefits.

The two concentration–response functions produce a broadly consistent spatial pattern, indicating that the geographical distribution of the estimated health benefits is primarily driven by the underlying spatial distribution of the changes in pollutant concentrations and exposed population. Nevertheless, differences in the magnitude of the estimated impacts are observed between the two functions. These differences reflect the distinct epidemiological parameters and population age ranges associated with each concentration–response function.

Overall, the similarity between the two maps strengthens the interpretation of the spatial results: while the choice of epidemiological function affects the absolute magnitude of the estimated mortality benefit, the main geographical pattern of health improvement remains broadly consistent.



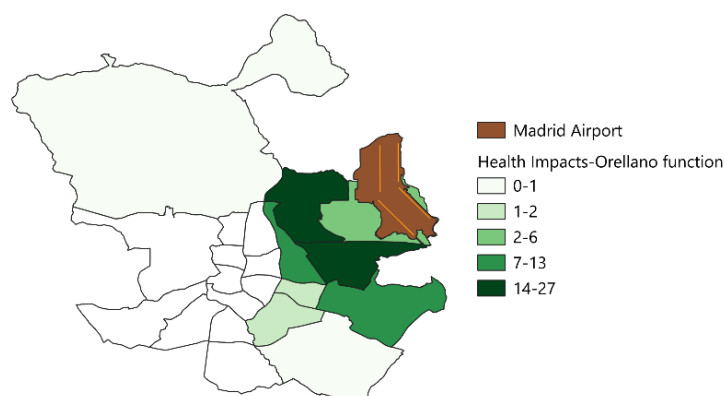


Figure 96 – Estimated avoided all-cause mortality attributable to PM reduction – Madrid Airport, 40% INDIGO solution scenario (Orellano et al., 2024).

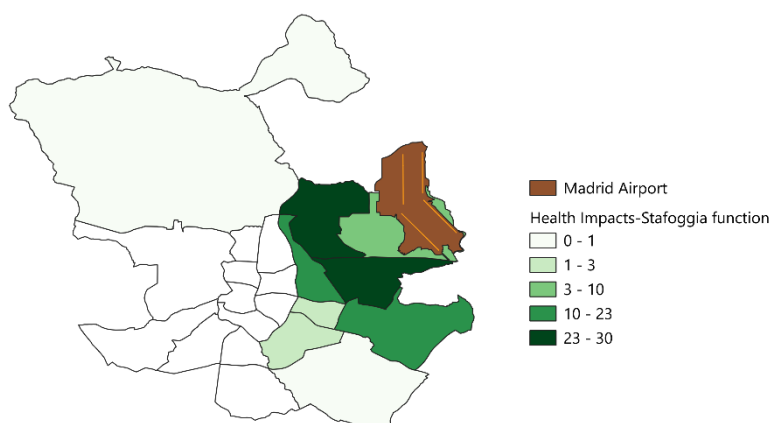


Figure 97 – Estimated avoided all-cause mortality attributable to PM reduction – Madrid Airport, 40% INDIGO solution scenario (Stafoggia et al., 2024).

6.4.1.1.2. Lung cancer mortality

Solution	Concentration– response function	Age range	Population considered	Estimated avoided deaths
10%	<i>Orellano et al.</i>	0–99	1465590	40
20%	<i>Orellano et al.</i>	0–99	1465590	59
30%	<i>Orellano et al.</i>	0–99	1465590	92
40%	<i>Orellano et al.</i>	0–99	1465590	104

Table 103 – Estimated avoided lung cancer deaths across INDIGO solution scenarios —Orellano et al.

The results show a progressive improvement in lung cancer mortality benefits as the introduction of INDIGO increases. However, the evolution is not linear, indicating that higher



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fleet replacement does not translate proportionally into additional health benefits. This behaviour reflects the combined influence of changes in pollutant concentrations and population exposure across the study area.

6.4.1.2. Nitrogen oxides (NO_x) results

6.4.1.2.1. All-cause mortality

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Kasdagli et al.</i>	0–99	1465590	18
<i>Stafoggia et al.</i>	30–99	1019268	15

Table 104 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 10% INDIGO solution scenario in Madrid

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Kasdagli et al.</i>	0–99	1465590	32
<i>Stafoggia et al.</i>	30–99	1019268	27

Table 105 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 20% INDIGO solution scenario in Madrid

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Kasdagli et al.</i>	0–99	1465590	85
<i>Stafoggia et al.</i>	30–99	1019268	72

Table 106 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 30% INDIGO solution scenario in Madrid

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Kasdagli et al.</i>	0–99	1465590	100
<i>Stafoggia et al.</i>	30–99	1019268	85

Table 107 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 40% INDIGO solution scenario in Madrid



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The NO_x-related all-cause mortality results show a clear increase in health benefits as INDIGO fleet introduction rises. Both concentration–response functions display the same overall trend, with progressively higher avoided mortality from Solution 10 to 40.

The increase is not uniform across the scenarios. The most pronounced improvement is observed between Solution 20 and 30, while the additional benefit from Solution 30 to Solution 40 is comparatively smaller. As expected, this progression is consistent with the general pattern observed in the other airport case studies.

The figures below show the spatial distribution of the estimated health benefits across Madrid districts, obtained using the Kasdagli et al. and Stafoggia et al. concentration–response functions.

The spatial distribution of the NO_x-related all-cause mortality benefits shows a clear concentration of the estimated impacts in the eastern and north-eastern areas of Madrid, particularly in districts located around and immediately west of Madrid Airport. In contrast, several central and south-western districts show comparatively small or negligible benefits.

The two concentration–response functions produce very similar spatial patterns, indicating that the geographical distribution of the estimated health benefits is consistent regardless of the epidemiological function applied. Kasdagli et al. generally produces higher absolute estimates than Stafoggia et al., in agreement with the results presented in the corresponding tables, while the districts showing the greatest and lowest benefits remain broadly the same.

Overall, the maps confirm that the main differences between the two functions concern the magnitude of the estimated health impact rather than its spatial distribution.

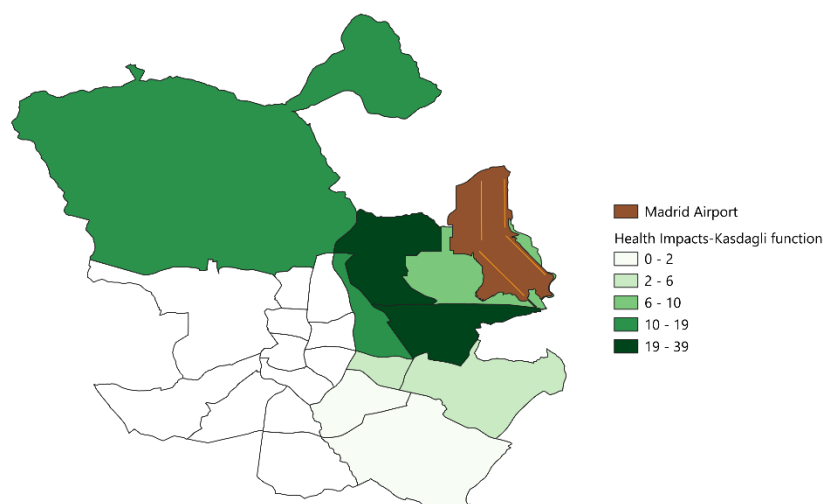


Figure 98 Estimated avoided all-cause mortality attributable to NO_x reduction – Madrid Airport, 40% INDIGO solution scenario (Kasdagli et al., 2024).



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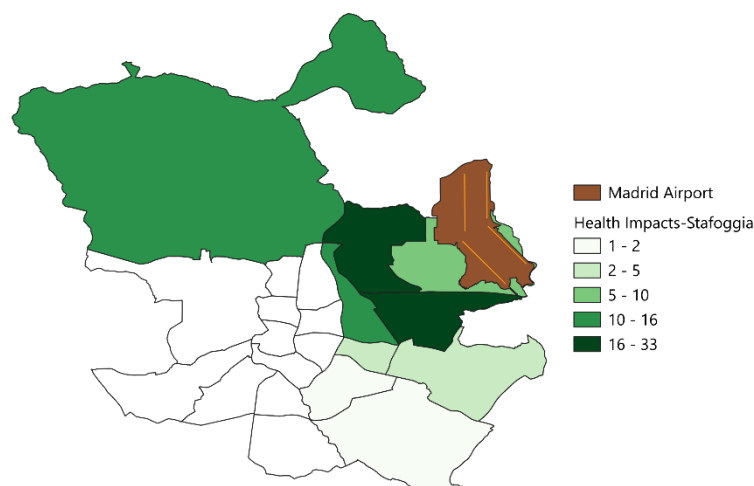


Figure 99 Estimated avoided all-cause mortality attributable to NO_x reduction – Madrid Airport, 40% INDIGO solution scenario (Stafoggia et al., 2024).

6.4.1.2.2. Respiratory mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al.	0–99	1465590	14
20%	Kasdagli et al.	0–99	1465590	25
30%	Kasdagli et al.	0–99	1465590	65
40%	Kasdagli et al.	0–99	1465590	77

Table 108 – Estimated avoided respiratory deaths across INDIGO solution scenarios (Kasdagli et al.)

The respiratory mortality results show a clear increase in estimated health benefits as INDIGO fleet replacement rises. The progression is particularly pronounced between Solution 20 and 30, while the additional improvement from Solution 30 to 40 is more moderate. As expected, this evolution is consistent with the pattern observed for NO_x-related all-cause mortality and with the general trend identified across the other airport case studies. Overall, the results indicate a progressively greater reduction in respiratory mortality with increasing INDIGO introduction.



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6.4.1.2.3. Cardiovascular mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al.	0–99	1465590	16
20%	Kasdagli et al.	0–99	1465590	28
30%	Kasdagli et al.	0–99	1465590	74
40%	Kasdagli et al.	0–99	1465590	87

Table 109 – Estimated avoided cardiovascular deaths across INDIGO solution scenarios (Kasdagli et al.)

The cardiovascular mortality results show a consistent increase in avoided deaths across the four INDIGO scenarios. As for respiratory mortality, the most pronounced improvement occurs between Solution 20 and 30, followed by a smaller additional increase at Solution 40. The cardiovascular benefits are slightly higher than those estimated for respiratory mortality across all replacement levels. Overall, the results confirm the positive progression observed for the other NO_x-related mortality endpoints, with the greatest health benefit obtained under the highest INDIGO replacement scenario.

6.4.1.3. Overall assessment

For Madrid, the health results under the 40% INDIGO scenario are summarised below as the minimum–maximum range of estimated avoided all-cause deaths obtained from the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals.

PM and NO_x show benefits of a similar magnitude, with overlapping ranges, while the NO_x estimates display greater variation between functions. Neither pollutant therefore consistently yields higher benefits across the functions applied. The results represent separate estimates of mortality benefits and should not be added together.

Pollutant	Concentration–response functions considered	Estimated range of avoided deaths
PM	Orellano et al.; Stafoggia et al.	86-94
NO_x	Kasdagli et al.; Stafoggia et al.	85-100

Table 110 – Summary of estimated avoided deaths by pollutant for Madrid Airport under the 40% INDIGO solution scenario



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6.4.2. Noise impact on population

Following the proposed methodology from WHO's guidelines (see section 3.6.1.7.) and applying them to Madrid's airport, the noise impact on population assessment has been carried out, in first place, by detecting the zones where population is exposed either to a LDEN above 45 dB (A) or to a Lnight above 40 dB (A).

Scenario	Population exposed to more than 45 dBA LDEN (inhabitants)	Average reduction (%)
Reference	165127	-
Solution 10%	136261	17
Solution 20%	132029	20
Solution 30%	124065	25
Solution 40%	113419	31

Table 111. Population above 45 dBA LDEN at MAD

The results show a progressive reduction in the population affected by aircraft noise as the number of aircraft replaced by INDIGO increases.

Scenario	Population exposed to more than 40 dBA Lnight (inhabitants)	Average reduction (%)
Reference	106747	-
Solution 10%	91630	14
Solution 20%	90789	15
Solution 30%	73984	31
Solution 40%	54729	49

Table 112. Population above 40 dBA Lnight at MAD

At night, same trend as LDEN values is observed. The overall reduction is slightly higher than the all-day results, due to the fact that most of the airport operations take place during the daytime and only certain aircraft models (more efficient and less noisy) are allowed to operate during the night-time.

The results regarding annoyance on population are presented below:



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Scenario	Population annoyed (inhabitants)	Average reduction (%)
Reference	34649	-
Solution 10%	28592	17
Solution 20%	27704	20
Solution 30%	26033	25
Solution 40%	23799	31

Table 113. Population annoyed at MAD

The population considered annoyed by aircraft noise shows a similar trend according to the LDEN above 45 dBA results.

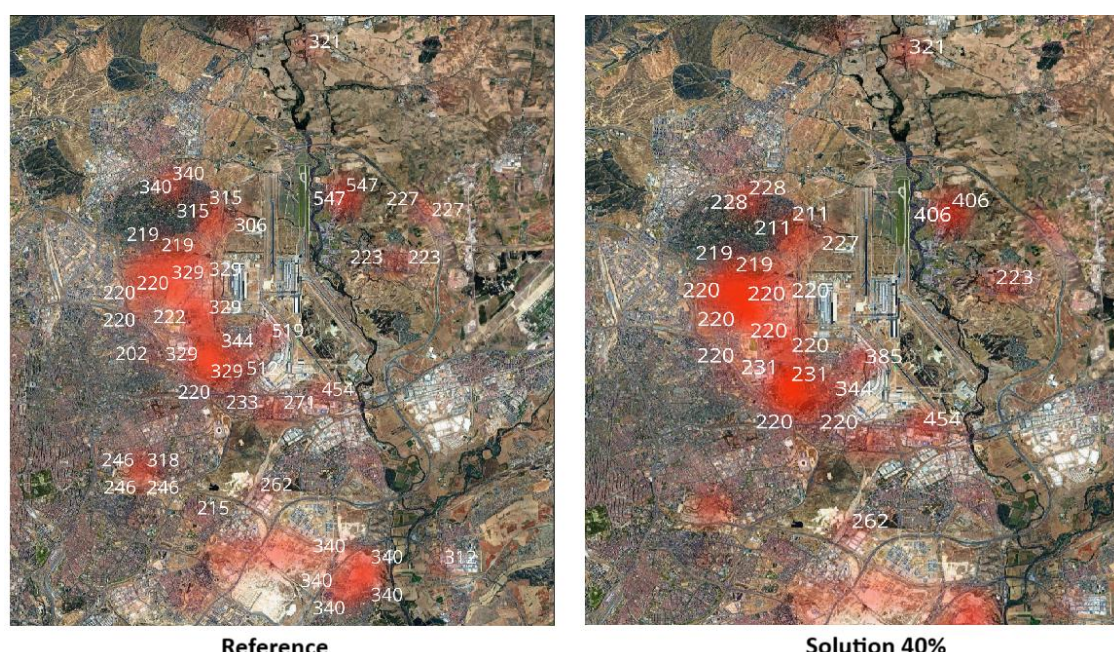


Figure 100. Spatial distribution of annoyed population both in Reference and Solution scenarios at MAD

The spatial distribution shown in the maps is consistent with these overall figures. In the Reference scenario, the affected population is more concentrated around the main areas influenced by the airport and its flight paths (with a higher concentration in the western neighbourhoods (especially Barajas and Alameda de Osuna), with several locations showing relatively high values. Under Solution 40% scenario, the areas with the highest concentrations of affected population become clearly less extensive and less intense, although some localised areas of significant impact remain.

The table below shows the results on sleep disturbance:



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Scenario	Population affected by sleep disturbance (inhabitants)	Average reduction (%)
Reference	13339	-
Solution 10%	11450	14
Solution 20%	11345	15
Solution 30%	9245	31
Solution 40%	6839	49

Table 114. HSD at MAD

The figure below shows the spatial hotspots regarding sleep disturbance:

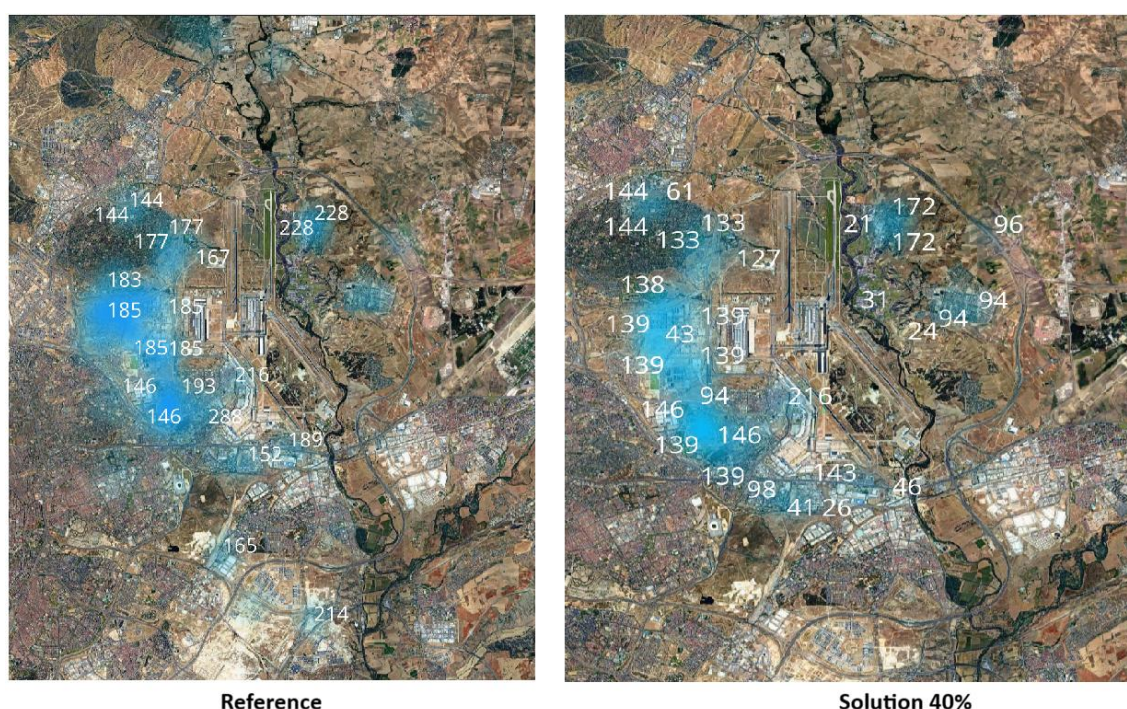


Figure 101. Spatial distribution of sleep disturbance on population both in Reference and Solution scenarios at MAD

In Madrid's airport Reference scenario, approximately 165127 inhabitants are exposed to aircraft noise above the WHO guideline level of 45 dBA LDEN. In Solution 40% scenario, this figure decreases to 113419 inhabitants, representing a 31% reduction in the population exposed above the WHO guideline value. This reduction indicates a substantial decrease in the number of inhabitants potentially exposed to noise levels associated with increased health risks according to the WHO assessment framework.

The effect is even more pronounced during the night. The population exposed to levels above 40 dBA Night decreases from 106747 inhabitants in the reference scenario to 54729 under most optimistic scenario, corresponding to a 49% reduction. This is particularly



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relevant from a health perspective because night-time aircraft noise is specifically associated by WHO with sleep disturbance, and the WHO guideline identifies 40 dBA Lnight as the recommended exposure level.

The estimated population affected by sleep disturbance follows the same trend, decreasing from 13339 inhabitants in the Reference scenario to 6839 in Solution 40% scenario, also representing a 49% reduction. This consistency between the reduction in the population above the 40 dBA Lnight threshold and the estimated population experiencing sleep disturbance reinforces the relevance of the proposed solution in terms of potential night-time health benefits.

Similarly, the population classified as annoyed by aircraft noise decreases from 34649 to 23799 inhabitants, corresponding to a 31% reduction. Annoyance is one of the health outcomes specifically considered in the WHO guidelines, and WHO identifies aircraft noise exposure above the 45 dBA LDEN guideline level as being associated with increased annoyance.

The spatial results are consistent with these numerical findings. The Reference represented results show a wider and more continuous distribution of population affected by high noise levels, particularly around the main airport flight paths (particularly to the neighbourhoods located on the West side of these paths). Under Solution 40% scenario, the areas with higher values become more limited, and the concentration of affected population is visibly reduced. This indicates that the benefits are not restricted to a reduction in the overall number of affected inhabitants, but also involve a spatial reduction of the areas where the population is exposed to noise levels above the WHO health-based guidelines.

Overall, Solution 40% scenario results in a 31% reduction in the population exposed above 45 dBA LDEN and a 49% reduction in both the population exposed above 40 dBA Lnight and the population affected by sleep disturbance. These results indicate a substantial reduction in the population potentially exposed to noise levels associated with adverse health effects, particularly during the night.

This reduction in aircraft noise exposure can contribute to improved living conditions and quality of life for the population living in the areas surrounding the airport, by providing a more favourable acoustic environment and reducing potential noise-related disturbance. Furthermore, lower exposure to aircraft noise may increase the residential attractiveness of the affected areas and potentially contribute positively to residential property values, although the actual effect on property values would also depend on other factors affecting the local housing market.

6.5. Barcelona airport

The health impact assessment for Barcelona Airport evaluates the potential population health benefits associated with changes in local air quality under the INDIGO scenarios relative to the reference configuration. The analysis considers the ten administrative districts of Barcelona, combining modelled pollutant concentrations with population and baseline mortality data to estimate changes in premature mortality.



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The assessment follows the methodological framework applied to the other airport case studies, considering particulate matter (PM) and nitrogen oxides (NO_x) under the four INDIGO solution scenarios. For Barcelona, the So and Andersen et al. concentration–response function is excluded from the assessment, on a more restricted population group and was therefore considered less representative of the population included in this case study.

The results presented in the following sections therefore cover the remaining functions and the mortality endpoints supported by the available input data.

District-level estimates provide insight into the spatial distribution of the potential health benefits within the city. Their interpretation should account for both changes in pollutant concentrations and the population exposed in each district.

In this way, the relatively low estimated health benefits for both PM and NO_x should be interpreted in light of the geographical scope of the assessment. Across all four airport case studies, the analysis focuses on populations within the selected city boundaries, excluding surrounding municipalities. This limitation is particularly relevant for Barcelona, as the airport is located outside the city’s administrative boundaries. Consequently, the assessment does not capture potential benefits for communities closer to the airport but outside the ten districts considered. The reported values therefore represent benefits within Barcelona city, rather than the total benefits across the airport’s wider area of influence.

6.5.1. LAQ impact on population

6.5.1.1. Particulate matter (PM) results

6.5.1.1.1. All-cause mortality

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	650611	3
<i>Stafoggia et al.</i>	30–99	446689	4

Table 115 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 10% INDIGO solution scenario in Barcelona airport

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	650611	4
<i>Stafoggia et al.</i>	30–99	446689	5

Table 116 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 20% INDIGO solution scenario in Barcelona airport



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<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	650611	4
<i>Stafoggia et al.</i>	30–99	446689	5

Table 117 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 30% INDIGO solution scenario in Barcelona airport

<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
<i>Orellano et al.</i>	0–99	650611	5
<i>Stafoggia et al.</i>	30–99	446689	6

Table 118 – Estimated avoided all-cause mortality associated with changes in PM concentrations under the 40% INDIGO solution scenario in Barcelona airport

The PM-related all-cause mortality results indicate modest health benefits within the population considered in Barcelona, with limited additional gains as INDIGO replacement increases. Both concentration–response functions show a similar progression across scenarios, with Stafoggia et al. producing slightly higher estimates than Orellano et al. The magnitude of these benefits should be interpreted in relation to both the concentration changes described in Chapter 5 and the geographical boundaries of the health impact assessment.

The limited differences between scenarios are consistent with the concentration reductions reported. A substantial reduction relative to the reference scenario is already achieved under Solution 10, whereas higher replacement levels provide comparatively small additional improvements. In particular, the average reductions under Solutions 20 and 30 are almost identical, which is consistent with the similar mortality benefits reported for these scenarios. As discussed in Chapter 5, this non-proportional progression may partly reflect the constraints on integrating INDIGO aircraft into Barcelona Airport traffic while complying with the replaceability and flyability rules defined in Assumption 3. Furthermore, reporting avoided deaths as whole numbers can conceal smaller differences between scenarios.

The low absolute number of estimated avoided deaths also needs to be considered in the context of the airport’s location outside Barcelona’s municipal boundaries. The health assessment covers the ten city districts, excluding neighboring municipalities and the immediate airport surroundings. Consequently, the areas experiencing the greatest concentration changes do not necessarily coincide with the population included in the health assessment. A substantial percentage reduction in airport-related concentrations therefore does not directly translate into a similarly large health benefit within Barcelona: the estimated benefit depends on the absolute concentration reduction experienced by the population considered.



An additional contextual factor is the use of departure procedures directing aircraft towards the sea to minimize noise impacts on surrounding communities. Such procedures are documented for Barcelona Airport. Routing aircraft over the sea may also help explain the limited overlap between some emission sources and the urban population assessed. However, its contribution to PM-related health benefits cannot be isolated from the present results, since ground-level concentrations also depend on emission altitude, meteorology and atmospheric dispersion.

The estimates should therefore be interpreted as benefits within the selected city boundaries and population coverage. They do not capture the full potential health benefit across the wider airport surroundings, where substantial concentration reductions may occur outside the geographical scope of this assessment.

The figures below present the spatial distribution of estimated avoided all-cause deaths under the 40% INDIGO scenario, using the Orellano et al. and Stafoggia et al. concentration–response functions. Barcelona’s municipal boundary and the airport’s location are shown within the wider geographical context of the Province of Barcelona. Both maps show a similar spatial pattern, with larger estimated benefits concentrated in the southern part of the city, closer to the airport. The airport itself lies outside the municipal boundary, highlighting that the assessment captures benefits within Barcelona city rather than across all surrounding municipalities potentially affected by airport emissions.

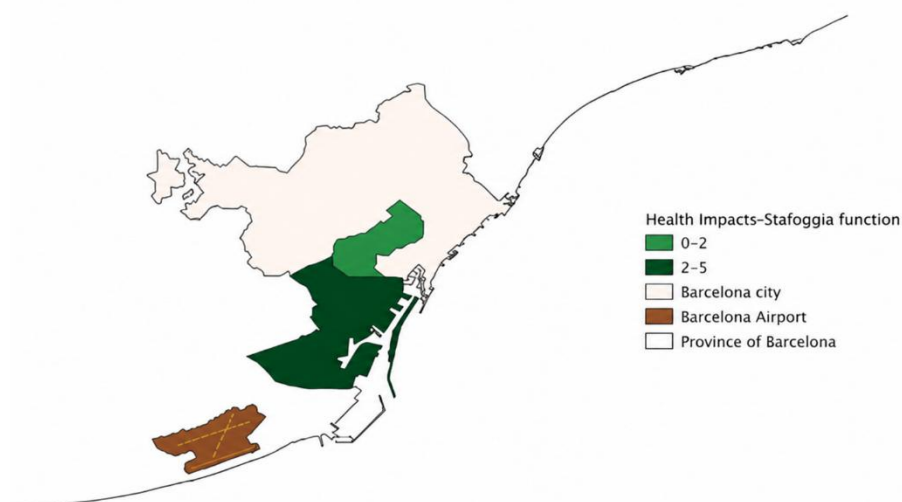


Figure 102 Estimated avoided all-cause mortality attributable to PM reduction – Barcelona Airport, 40% INDIGO solution scenario (Orellano et al., 2024).



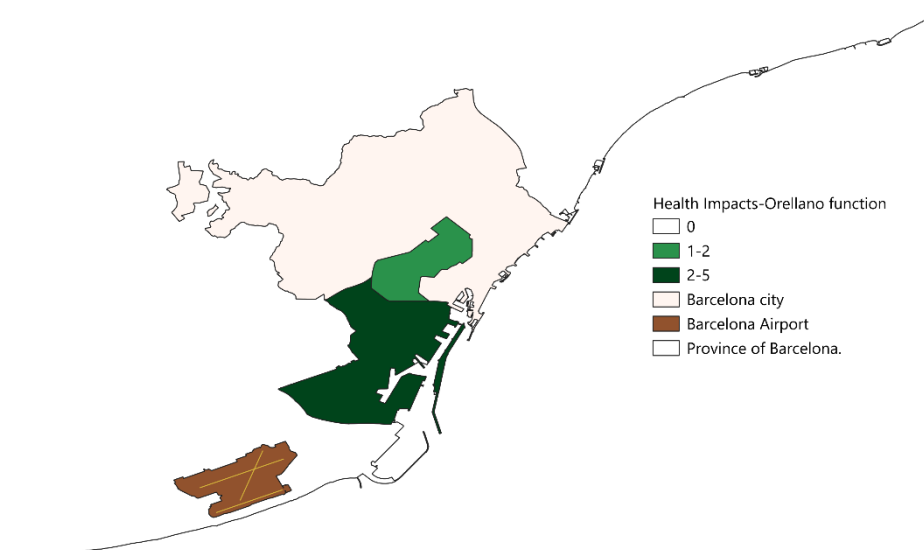


Figure 103 – Estimated avoided all-cause mortality attributable to PM reduction –Barcelona Airport, 40% INDIGO solution scenario (Stafoggia et al., 2024).

6.5.1.1.2. Lung cancer mortality

Solution	Concentration–response function	Age range	Population considered	Estimated avoided deaths
10%	Orellano et al.	0–99	650611	< 1
20%	Orellano et al.	0–99	650611	1
30%	Orellano et al.	0–99	650611	1
40%	Orellano et al.	0–99	650611	1

Table 119 – Estimated avoided lung cancer deaths across INDIGO scenarios in Barcelona Airport — Orellano et al.

The estimated benefits for lung cancer mortality follow a similarly limited progression across the INDIGO scenarios. The increase from Solution 10 to 20 is followed by broadly stable results at the reporting precision adopted. Identical rounded values under solutions 20, 30 and 40, do not necessarily indicate identical health benefits, as smaller differences may be concealed by rounding.

This pattern is consistent with the limited additional reductions in PM concentrations described above and with the geographical scope of the assessment. The results suggest a small potential reduction in lung cancer mortality within the population considered, with relatively modest additional benefits as number of INDIGO aircraft increases. Estimates below one avoided death represent a reduction in the expected number of deaths across the assessed population and should not be interpreted as an absence of benefit.



6.5.1.2. Nitrogen oxides (NO_x) results

6.5.1.2.1. All-cause mortality

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	650611	< 1
<i>Stafoggia et al.</i>	30–99	446689	< 1

Table 120 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 10% INDIGO solution scenario in Barcelona

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	650611	< 1
<i>Stafoggia et al.</i>	30–99	446689	< 1

Table 121 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 20% INDIGO solution scenario in Barcelona

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	650611	< 1
<i>Stafoggia et al.</i>	30–99	446689	< 1

Table 122 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 30% INDIGO solution scenario in Barcelona

Concentration–response function	Age range	Population considered	Estimated avoided deaths
<i>Kasdagli et al.</i>	0–99	650611	< 1
<i>Stafoggia et al.</i>	30–99	446689	< 1

Table 123 – Estimated gross avoided all-cause mortality associated with NO_x concentration changes under the 40% INDIGO solution scenario in Barcelona

The NO_x-related health assessment indicates small, estimated mortality benefits within the population considered in Barcelona. All reported estimates remain below one avoided death, both for all-cause mortality and for the cardiovascular and respiratory endpoints. These fractional estimates represent reductions in the expected number of deaths across



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the assessed population and should not be interpreted as an absence of benefit. However, reporting all results as “< 1” prevents a detailed comparison between scenarios or concentration–response functions.

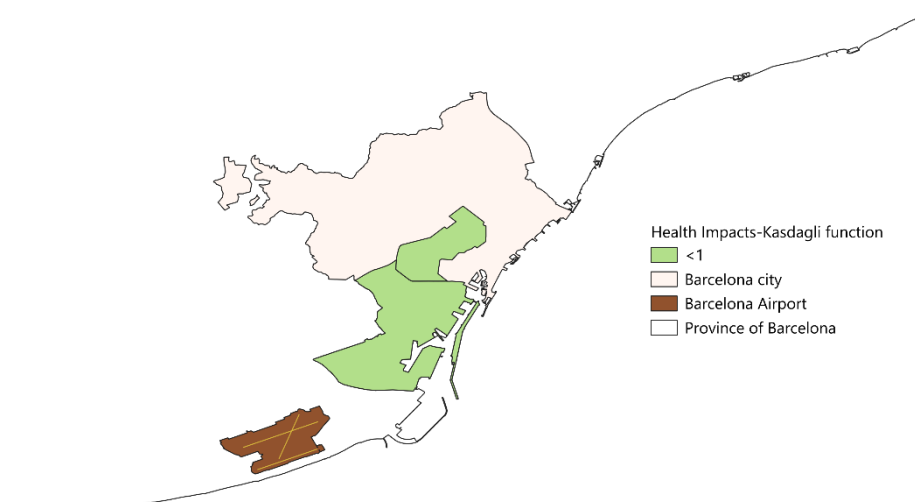
The concentration results presented in Chapter 5 provide context for the limited additional benefits expected at higher INDIGO solution levels. As shown in

Table 52, most of the average NO_x concentration reduction is already achieved under Solution 10, with only modest additional improvements in subsequent scenarios. This suggests limited scope for further health gains as solution increases, although the magnitude of these gains depends on where the additional concentration reductions occur relative to the exposed population.

The substantial percentage reductions reported in Chapter 5 and the small mortality benefits are therefore not necessarily contradictory: the former describe changes in concentrations across the modelling domain, whereas the latter depend on the absolute concentration changes experienced by the population included in the assessment. The results indicate a limited estimated health benefit within the selected city boundaries, without capturing potential benefits across the wider airport surroundings.

Although the estimated benefits do not reach one avoided death, they remain positive and reflect a small, modelled reduction in mortality risk. Since avoided deaths are expressed as expected values across a population, estimates below one should not be treated as zero. The “< 1” notation therefore indicates a benefit below one expected avoided death, rather than a null effect.

The figure below shows the spatial distribution of estimated NO_x-related avoided all-cause deaths under the 40% INDIGO scenario, using the Kasdagli et al. and Stafoggia et al, concentration–response functions. The highlighted districts lie in the southern part of Barcelona, closer to the airport, and all fall within the same category of less than one avoided death. This broad classification does not allow differences between districts to be distinguished. The map also illustrates the geographical scope of the assessment, which excludes potential health benefits in neighbouring municipalities surrounding the airport.



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Figure 104 – Estimated avoided all-cause mortality attributable to NO_x reduction – Barcelona Airport, 40% INDIGO solution scenario (Kasdagli et al., 2024).

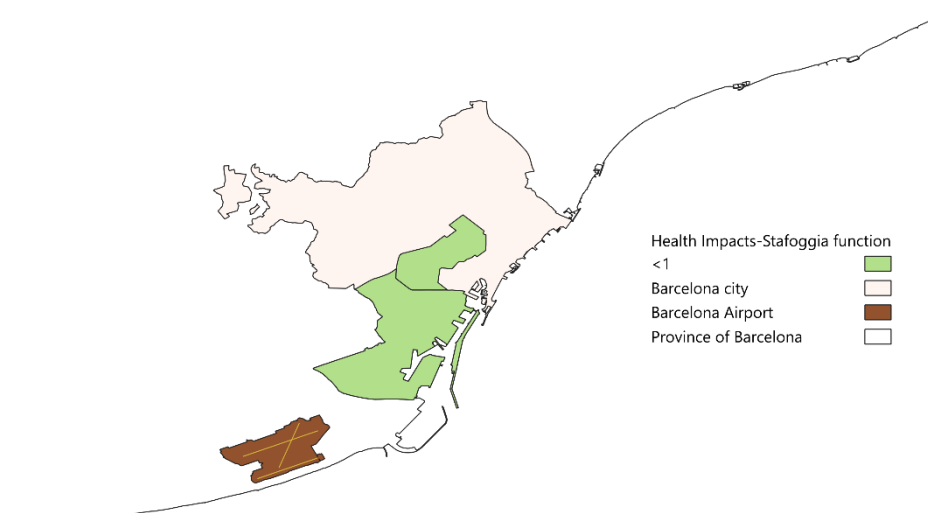


Figure 105 – Estimated avoided all-cause mortality attributable to NO_x reduction –Barcelona Airport, 40% INDIGO solution scenario (Stafoggia et al., 2024).

6.5.1.2.2. Cardiovascular mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al.	0–99	650611	< 1
20%	Kasdagli et al.	0–99	650611	< 1
30%	Kasdagli et al.	0–99	650611	< 1
40%	Kasdagli et al.	0–99	650611	< 1

Table 124 – Estimated avoided cardiovascular deaths across INDIGO solution scenarios in Barcelona airport (Kasdagli et al.)

The estimated reductions in NO_x-related cardiovascular mortality remain below one avoided death across all INDIGO scenarios. These fractional estimates indicate a small reduction in expected mortality within the population considered, rather than an absence of benefit. However, reporting all results as “<1” does not allow differences between scenarios to be assessed. The findings should also be interpreted within the geographical scope of the analysis, which excludes communities outside Barcelona’s municipal boundaries.



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6.5.1.2.3. Respiratory mortality

<i>Solution</i>	<i>Concentration–response function</i>	<i>Age range</i>	<i>Population considered</i>	<i>Estimated avoided deaths</i>
10%	Kasdagli et al.	0–99	650611	< 1
20%	Kasdagli et al.	0–99	650611	< 1
30%	Kasdagli et al.	0–99	650611	< 1
40%	Kasdagli et al.	0–99	650611	< 1

Table 125 – Estimated avoided respiratory deaths across INDIGO scenarios in Barcelona airport — Kasdagli et al.

The respiratory mortality assessment similarly indicates limited estimated benefits, with fewer than one avoided death under each INDIGO scenario. The reporting format prevents a clear comparison of the additional benefits associated with increasing fleet replacement. These results refer specifically to the population included in the assessment and do not capture potential mortality benefits in neighbouring municipalities closer to the airport.

6.5.1.3. Overall assessment

For Barcelona, the health results under the 40% INDIGO scenario are summarised below using the minimum–maximum range of estimated avoided all-cause deaths across the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals. For NO_x, both estimates remain below one avoided death and are therefore reported as “< 1”.

The estimated benefits are greater for PM than for NO_x across the functions applied. Nevertheless, the fractional NO_x estimates represent a small reduction in expected mortality rather than an absence of benefit. These findings refer exclusively to the population included within Barcelona’s ten districts and exclude potential benefits in neighbouring municipalities closer to the airport. Results for the two pollutants should not be added together.

Pollutant	Concentration–response functions considered	Estimated range of avoided deaths
PM	Orellano et al.; Stafoggia et al.	5-6
NO _x	Kasdagli et al.; Stafoggia et al.	< 1

Table 126 – Summary of estimated avoided deaths by pollutant for Barcelona Airport under the 40% INDIGO solution scenario



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6.5.2. Noise impact on population

Following the proposed methodology from WHO's guidelines (see section 3.6.1.7.) and applying them to Barcelona's airport, the noise impact on population assessment has been carried out, in first place, by detecting the zones where population is exposed either to a LDEN above 45 dB (A) or to a Lnight above 40 dB (A).

Scenario	Population exposed to more than 45 dBA LDEN (inhabitants)	Average reduction (%)
Reference	99637	-
Solution 10%	96110	4
Solution 20%	92417	7
Solution 30%	88127	12
Solution 40%	82743	17

Table 127. Population above 45 dBA LDEN at BCN

The results show a progressive reduction in the population affected by aircraft noise as the number of aircraft replaced by INDIGO increases, but less pronounced than in previous scenarios.

Scenario	Population exposed to more than 40 dBA Lnight (inhabitants)	Average reduction (%)
Reference	99629	-
Solution 10%	99428	< 1
Solution 20%	97304	2
Solution 30%	94705	5
Solution 40%	91142	9

Table 128. Population above 40 dBA Lnight at BCN

At night, different trend as LDEN values is observed. The overall reduction is lower than the all-day results, due to the fact that most of the airport operations during the night take place in Runway 02 (which is oriented to the Mediterranean Sea, moving aircraft away from populated areas towards the sea) and only certain flights are operating in parallel runways.

The results regarding annoyance on population are presented below:



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Scenario	Population annoyed (inhabitants)	Average reduction (%)
Reference	28056	-
Solution 10%	27063	4
Solution 20%	26023	7
Solution 30%	24815	12
Solution 40%	23299	17

Table 129. Population annoyed at BCN

The population considered annoyed by aircraft noise shows a similar trend according to the LDEN above 45 dBA results.



Figure 106. Spatial distribution of annoyed population both in Reference and Solution scenarios at BCN

The spatial distribution shown in the maps is consistent with these overall figures. In the Reference scenario, the affected population is greater around the main areas influenced by the airport and its flight paths (with a higher concentration in the surrounding neighbourhoods (especially Gavá, Castelldefels and El Prat de Llobregat), with several locations showing relatively high values. Under Solution 40% scenario, the areas with the highest concentrations of affected population become clearly less intense, although the extension of these areas remains almost the same.

The table below shows the results on sleep disturbance:

Scenario	Population affected by sleep disturbance (inhabitants)	Average reduction (%)
Reference	14874	-
Solution 10%	14844	< 1



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Scenario	Population affected by sleep disturbance (inhabitants)	Average reduction (%)
Solution 20%	14527	2
Solution 30%	14139	5
Solution 40%	13607	9

Table 130. HSD at BCN

The figure below shows the spatial hotspots regarding sleep disturbance:



Figure 107. Spatial distribution of sleep disturbance on population both in Reference and Solution scenarios at BCN

The results for annoyance and sleep disturbance (HSD) at Barcelona Airport show a more limited reduction compared with the results obtained for Riga and Madrid. This behaviour is consistent with the existing operational configuration of this airport, where the night-time runway configuration (Runway 02) already directs aircraft predominantly towards the Mediterranean Sea, considerably limiting the exposure of the surrounding residential areas.

Regarding annoyance, the estimated affected population decreases from 28056 inhabitants in the Reference scenario to 23299 inhabitants under Solution 40% scenario, corresponding to a 17% reduction. The effect increases progressively with the solution level, although the overall reduction remains more moderate than those observed for Riga, Dortmund and Madrid. This is consistent with the fact that the proposed measure consists of aircraft replacement while maintaining the existing flight procedures and routes (which are already designed to minimize the noise impact on populated areas). Consequently, the solution mainly reduces the noise generated by aircraft operating along the existing procedures, without substantially changing the spatial distribution of the affected population.

The results for sleep disturbance are even less variable. The population affected by HSD decreases from 14874 inhabitants in the Reference scenario to 13607 under most optimal solution, corresponding to a reduction of only 9%. The intermediate solutions produce reductions of less than 1%, 2% and 5% for Solutions 10%, 20% and 30%, respectively.



This comparatively small effect is particularly relevant when interpreting the night-time results. During the night, the runway configuration oriented towards the sea is preferentially used, meaning that the flight paths producing the greatest potential exposure over the surrounding populated areas (parallel runways) are hardly ever used. As a result, the baseline night-time noise footprint over residential areas is already relatively constrained. The introduction of INDIGO can therefore only produce a limited additional reduction in the population affected by sleep disturbance.

This also explains the difference between the overall LDEN results and the night-time indicators (L_{night} above 40 dBA and HSD). While Solution 40% reduces the population exposed to more than 45 dBA LDEN by 17%, the reduction in population exposed to more than 40 dBA L_{night} is only 9%, with the same reduction observed for the estimated population affected by sleep disturbance. The smaller variation is therefore not necessarily indicative of a lower effectiveness of the aircraft replacement itself, but rather reflects the lower sensitivity of the existing night-time exposure to changes in aircraft noise levels, given the prevailing runway and flight-path configuration.

The spatial distribution of HSD is consistent with these findings. The Reference and Solution 40% scenarios maps show similar overall spatial patterns, with the main affected areas remaining broadly in the same locations (Castelldefels, Gavá and El Prat de Llobregat). The differences are primarily related to a reduction in the magnitude of the affected population rather than to a substantial displacement or contraction of the affected area.

From a health perspective, the results can be interpreted in the context of the WHO Environmental Noise Guidelines, which identify 40 dBA L_{night} for aircraft noise as the recommended night-time exposure level due to the potential for adverse effects on sleep. The reduction from 14874 to 13607 inhabitants affected by sleep disturbance therefore indicates a positive, although comparatively limited, additional benefit from the aircraft replacement scenario.

From a quality-of-life perspective, the reduction in aircraft noise achieved under Solution 40% scenario can contribute to improved living conditions for the population surrounding Barcelona Airport, particularly by reducing overall noise exposure and associated annoyance. However, the results also indicate that the potential for further improvement through aircraft replacement alone is relatively limited, especially during the night. The analysis suggests that achieving greater benefits for the surrounding population would require not only a continued increase in the use of INDIGO aircraft, but also further consideration of operational measures and flight procedures that maximise the use of routes over the Mediterranean Sea, where feasible. Such measures could provide a greater reduction in exposure over densely populated areas, particularly during periods when the existing runway configuration does not already provide the same level of protection.

The ideal scenario, combining continued fleet renewal with additional operational procedures favouring flight paths over the Mediterranean Sea, could further enhance these benefits by creating positive synergies between technological and operational noise mitigation measures. In this context, the combination of INDIGO aircraft and procedures that minimise overflight of densely populated areas could provide a greater overall reduction in aircraft noise exposure than either measure considered independently, with corresponding benefits for annoyance, sleep disturbance, living conditions and quality of life.



7. Economic impact

The economic assessment quantifies the monetary value of mortality benefits associated with changes in local air quality (LAQ) under the INDIGO scenarios relative to the reference configuration. As defined in the assumptions presented in Chapter 1, the economic valuation performed in this chapter is restricted to mortality impacts associated with changes in local air quality. Noise-related health impacts and morbidity outcomes are excluded from the economic valuation. Consequently, the monetised benefits reported in the following sections represent exclusively the economic value associated with the estimated changes in premature mortality attributable to LAQ improvements.

The health benefits conferred on individuals by a reduction in pollution are actually reductions in the risk of having to endure certain health problems. Monetizing the benefits of a reduction in air pollution involves estimating society's willingness to pay (WTP) for these reductions in risk, or the observed Cost of Illness (COI) for an effect and is typically referred to as valuation. BenMAP CE uses valuation functions to estimate the monetized benefits of reducing air pollution.

Valuation Functions are used by BenMAP-CE to estimate the economic values of changes in the incidence of health effects. In the context of human health benefits assessment, these functions help express society's preferences for avoiding certain health effects as an economic value (e.g., in U.S. dollars).

For mortality endpoints, BenMAP-CE generally estimates monetized benefits by using the Value of Statistical Life (VSL), a WTP-based estimate derived from an extensive literature of observed or elicited estimates of the monetary value that an individual is willing to exchange for small reductions in his or her risk of death. It's important to underline that it does not represent the value of the life of any one specified individual.

This term is easily misinterpreted and should be carefully described when used in benefit analysis. VSL is the aggregate dollar amount that a large group of people would be willing to pay for a reduction in their individual risks of dying in a year, such that we would expect one fewer death among the group during that year on average. The basic assumption underlying the VSL approach is that equal increments in fatality risks are valued equally. For similar reasons, the VSL approach is only appropriate for marginal changes in the risk of death and should not be used to value more significant changes. Because changes in individual fatality risks resulting from environmental regulation are typically very small, the VSL approach is usually acceptable for these types of benefit analyses [21].

The conceptual basis adopted in this study is consistent with the approach described by the U.S. Environmental Protection Agency (EPA). The EPA guidance on mortality risk valuation was therefore used as a conceptual reference for interpreting the VSL approach and its application within environmental benefit–cost analysis.

For the quantitative economic assessment, however, the VSL values were derived following the methodology developed by the OECD Environment Directorate (OECD-ENV), as



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implemented in the OECD SPHeP-NCDs framework. The OECD methodology establishes a base VSL of USD 3 million at 2005 prices as the starting point for the calculation of country-specific VSL values. This reference value originates from the OECD assessment of stated-preference studies on individuals' willingness to pay for reductions in mortality risks. The OECD methodology subsequently transfers this reference value to individual countries by accounting for differences in income relative to the OECD average using purchasing-power-parity (PPP)-adjusted GDP per capita and an income-elasticity adjustment. [22]

Accordingly, the USD 3 million value should not be interpreted as the final VSL directly applied to each airport case study. Instead, it constitutes the 2005 OECD reference value from which the corresponding country-specific VSL is derived. This makes it possible to account for differences in economic conditions between the European countries considered in the INDIGO case studies while maintaining a common and consistent methodological basis.

The country-specific VSL at the 2005 price level was calculated as follows:

$$VSL_{C,2005} = VSL_{OECD,2005} \times \left(\frac{Y_{C,2005}}{Y_{OECD,2005}} \right)^{\beta}$$

Where $VSL_{OECD,2005}$ is the OECD reference VSL of USD 3 million, $Y_{C,2005}$ is the GDP per capita of country C in 2005 expressed in PPP-adjusted US dollars, $Y_{OECD,2005}$ is the corresponding OECD average GDP per capita, and β is the income elasticity of the VSL, set to 0.8. GDP per capita values were obtained from the OECD National Accounts database and expressed in US dollars per person, PPP converted.

Country	OECD reference VSL	Income elasticity	GDP per capita 2005 (USD PPP)	OECD GDP per capita 2005 (USD PPP)	Country-specific VSL (2005)
<i>Latvia</i>	USD 3 million	0.8	USD 12826.2	USD 30031.6	USD 1.519M
<i>Germany</i>	USD 3 million	0.8	USD 32763.6	USD 30031.6	USD 3.216M
<i>Spain</i>	USD 3 million	0.8	USD 27623.7	USD 30031.6	USD 2.806M

Table 131 – Country-specific VSL values derived from the OECD reference VSL at 2005 price levels

Since the health and economic assessment developed in this study refers to 2023, the resulting country-specific VSL values were subsequently adjusted to the 2023 price level. This adjustment ensures that mortality benefits are expressed consistently in 2023 monetary terms rather than in the original 2005 price level.

Two main adjustment factors are required to convert the VSL expressed with reference to the 2005 base year to values applicable to the 2023 assessment year.



First, an income growth adjustment is applied to account for changes in real income over time. In practical terms, the VSL is adjusted according to the growth in income per capita between the base year and the target year, considering the income elasticity of the VSL. This reflects the assumption that society's willingness to pay for reductions in mortality risk changes as income levels evolve. The resulting value therefore represents a country-specific VSL adjusted for the change in real income between 2005 and 2023.

Second, an inflation adjustment is required to express the resulting VSL at the 2023 price level. Within the present assessment, this adjustment is performed directly within BenMAP-CE through the inflation data incorporated into the valuation framework. BenMAP-CE uses the corresponding price index to convert the monetary value from its reference price year to the selected analysis year, thereby ensuring that the estimated mortality benefits are expressed consistently in 2023 monetary terms.

Finally, since the VSL values derived following the OECD-ENV methodology are expressed in US dollars, the resulting 2023 values are converted into euros using the corresponding USD/EUR exchange rate. The final VSL values used in the INDIGO economic assessment are therefore expressed in 2023 euros and incorporate both the income-growth adjustment and the inflation adjustment.

<i>Country</i>	<i>Real income growth 2005–2023, ΔY (%)</i>	<i>BenMAP inflation factor 2005–2023 [23]</i>	<i>USD-to-EUR conversion factor [0]</i>
<i>Germany</i>	1.1684	1.47	0.93
<i>Latvia</i>	1.4621	2.13	0.93
<i>Spain</i>	1.0685	1.43	0.93

Table 132 – Economic adjustment parameters applied to derive country-specific VSL values for the 2023 assessment year

<i>Country</i>	<i>VSL (Millions €)</i>
<i>Germany</i>	3.495
<i>Latvia</i>	2.065
<i>Spain</i>	2.788

Table 133 – Final VSL values converted to Euros



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7.1. Applicable metrics and indicators

INDIGO indicators			
Area	Type	Indicator	Metric
Economic assessment (LAQ)	PM-related mortality valuation	Monetised benefits of avoided premature mortality attributable to reduced PM concentrations	Total annual monetary benefit relative to the reference scenario (million €, 2023 prices)
Economic assessment (LAQ)	NOx-related mortality valuation	Monetised benefits of avoided premature mortality attributable to reduced NOx concentrations	Total annual monetary benefit relative to the reference scenario (million €, 2023 prices)

Table 134 – INDIGO economic indicators

The presented indicator is the monetised benefits of avoiding deaths of chapter 6, note that only the “all-cause” deaths are considered for this economic assessment, for each pollutant.

7.2. Results

7.2.1. Riga airport

The economic assessment quantifies the monetary value of mortality benefits associated with changes in local air quality (LAQ) under the INDIGO scenarios relative to the reference configuration.

Changes in pollutant concentrations between the reference and INDIGO scenarios are combined with population data, baseline mortality rates and the selected concentration–response functions to estimate avoided premature deaths. Economic valuation subsequently converts these health impacts into monetary benefits using the Value of a Statistical Life (VSL).

7.2.1.1. Particulate matter (PM) results

<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>So and Andersen et al.</i>	30–99	202.37
<i>Stafoggia et al.</i>	30–99	100.31
<i>Orellano et al.</i>	0–99	88.67

Table 135 - Total monetised benefit all-cause mortality benefits per district associated with PM under the 10% INDIGO scenario in Riga



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>So and Andersen et al.</i>	30–99	392.30
<i>Stafoggia et al.</i>	30–99	194.72
<i>Orellano et al.</i>	0–99	172.18

Table 136 – Total monetised all-cause mortality benefits across Riga associated with PM under the 20% INDIGO solution scenario

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>So and Andersen et al.</i>	30–99	786.45
<i>Stafoggia et al.</i>	30–99	391.36
<i>Orellano et al.</i>	0–99	346.13

Table 137 – Total monetised all-cause mortality benefits across Riga associated with PM under the 30% INDIGO scenario

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>So and Andersen et al.</i>	30–99	819.85
<i>Stafoggia et al.</i>	30–99	408.07
<i>Orellano et al.</i>	0–99	360.92

Table 138 – Total monetised all-cause mortality benefits across Riga associated with PM under the 40% INDIGO scenario

Overall, the monetised benefits associated with particulate matter increase with the share of INDIGO aircraft, confirming that the progressive introduction of the hybrid-electric configuration generates increasingly relevant economic benefits through avoided premature mortality. However, the progression is not proportional to the INDIGO introduction rate: a marked increase is observed between the 20% and 30% solution scenarios, while the additional benefit obtained when moving from 30% to 40% is comparatively limited.



7.2.1.2. Nitrogen oxides (NOx) results

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	47.96
<i>Kasdagli et al.</i>	0–99	54.66

Table 139 – Total monetised all-cause mortality benefits per district associated with NOx under the 10% INDIGO solution scenario in Riga

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	152.20
<i>Kasdagli et al.</i>	0–99	173.43

Table 140 – Total monetised all-cause mortality benefits per district associated with NOx under the 20% INDIGO solution scenario in Riga.

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	164.70
<i>Kasdagli et al.</i>	0–99	187.66

Table 141 – Total monetised all-cause mortality benefits per district associated with NOx under the 30% INDIGO solution scenario in Riga

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	172.22
<i>Kasdagli et al.</i>	0–99	196.24

Table 142 – Total monetised all-cause mortality benefits per district associated with NOx under the 40% INDIGO solution scenario in Riga

The monetised benefits associated with NOx also increase as the share of INDIGO aircraft rises, although the progression is clearly non-linear. The largest relative improvement occurs in the lower replacement scenarios, whereas the additional economic benefit becomes progressively smaller at higher levels of INDIGO introduction.

As for PM, this behaviour reflects the fact that fleet replacement and population exposure are not directly proportional. The differences in the incremental benefits among scenarios primarily reflect the concentration and exposure patterns generated by the modelled fleet configurations rather than a direct linear relationship between INDIGO introduction and avoided mortality.



7.2.1.3. Overall assessment

To summarise the SOL40 results, the table below presents the minimum–maximum range of estimated monetised all-cause mortality benefits obtained from the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals. PM-related benefits show a wider range than those associated with NO_x, indicating greater variability across the selected epidemiological functions.

Pollutant	Concentration-response function	Benefit range by pollutant (Million €)
PM	<i>Orellano et al.; Stafoggia et al.; So and Andersen et al.</i>	361-820
NO _x	<i>Kasdagli et al.; Stafoggia et al.</i>	172-196

Table 143 – Summary of monetised all-cause mortality benefits associated with PM and NO_x under the 40% INDIGO solution scenario in Riga

7.2.2. Dortmund airport

The following sections present the estimated economic benefits associated with reductions in PM- and NO_x-related all-cause mortality under the INDIGO scenarios for Dortmund, relative to the reference configuration. Benefits are expressed in millions of euros and reported separately for each concentration–response function. The preliminary results indicate increasing benefits with fleet replacement, although the progression differs between pollutants: PM benefits rise most strongly between the 20% and 30% scenarios, whereas NO_x benefits increase across all scenarios.

7.2.2.1. Particulate matter (PM) result

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Orellano et al.</i>	0–99	13
<i>So and Andersen</i>	30–99	29.8
<i>Stafoggia et al.</i>	30–99	14.73

Table 144 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 10% INDIGO solution scenario in Dortmund



Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Orellano et al.</i>	0–99	13.3
<i>So and Andersen</i>	30–99	30.5
<i>Stafoggia et al.</i>	30–99	15.07

Table 145 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 20% INDIGO solution scenario in Dortmund

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Orellano et al.</i>	0–99	32.51
<i>So and Andersen</i>	30–99	74.37
<i>Stafoggia et al.</i>	30–99	36.85

Table 146 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 30% INDIGO solution scenario in Dortmund

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Orellano et al.</i>	0–99	32.65
<i>So and Andersen</i>	30–99	74.70
<i>Stafoggia et al.</i>	30–99	37.00

Table 147 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 40% INDIGO solution scenario in Dortmund

The preliminary PM results for Dortmund show a distinctly non-linear progression in monetised benefits, with most of the improvement concentrated between the 20% and 30% INDIGO scenarios. The limited differences between 10% and 20%, and between 30% and 40%, suggest that additional fleet replacement does not consistently translate into comparable reductions in population exposure. All three concentration–response functions reproduce this pattern, although So and Andersen yields substantially higher benefits than Orellano et al. and Stafoggia et al.



7.2.2.2. Nitrogen oxides (NOx) results

<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
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<i>Kasdagli et al.</i>	0–99	29.18
<i>Stafoggia et al.</i>	30–99	25.63

Table 148 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 10% INDIGO solution scenario in Dortmund

<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
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<i>Kasdagli et al.</i>	0–99	45.25
<i>Stafoggia et al.</i>	30–99	39.77

Table 149 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 20% INDIGO solution scenario in Dortmund

<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
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<i>Kasdagli et al.</i>	0–99	50.18
<i>Stafoggia et al.</i>	30–99	44.10

Table 150 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 30% INDIGO solution scenario in Dortmund

<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
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<i>Kasdagli et al.</i>	0–99	57.33
<i>Stafoggia et al.</i>	30–99	50.40

Table 151 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 40% INDIGO solution scenario in Dortmund

For NOx, the estimated economic benefits increase across all INDIGO scenarios, with the largest incremental gain occurring between 10% and 20% fleet replacement. Further improvements are smaller, although the increase from 30% to 40% exceeds that observed between 20% and 30%. This pattern indicates an uneven progression rather than a steady decline in incremental benefits. Kasdagli et al. consistently yields higher estimates than Stafoggia et al., while both functions show closely aligned trends across scenarios.



7.2.2.3. Overall assessment

For Dortmund, the economic results under the 40% INDIGO scenario are summarised below as the minimum–maximum range of the estimates obtained from the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals.

Pollutant	Concentration-response function	Benefit range by pollutant (Million €)
PM	<i>Orellano et al.; Stafoggia et al.; So and Andersen et al.</i>	33-75
NOx	<i>Kasdagli et al.; Stafoggia et al.</i>	50-57

Table 152 – Range of estimated monetized all-cause mortality benefits by pollutant under the 40% INDIGO scenario in Dortmund

7.2.3. Madrid airport

The following sections present the estimated economic benefits associated with reductions in PM- and NOx-related all-cause mortality under the INDIGO scenarios for Madrid, relative to the reference configuration. Benefits are expressed in millions of euros and reported separately for each concentration–response function. Both pollutants show a non-linear increase in benefits with fleet replacement, with the largest improvement occurring between the 20% and 30% scenarios, particularly for NOx. Further gains are observed at 40%, although their magnitude is smaller.

7.2.3.1. Particulate matter (PM) result

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	41.28
<i>Orellano et al.</i>	0–99	36.57

Table 153 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 10% INDIGO solution scenario in Madrid

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	59.77
<i>Orellano et al.</i>	0–99	53

Table 154 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 20% INDIGO solution scenario in Madrid



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	90.73
<i>Orellano et al.</i>	0–99	80.48

Table 155 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 30% INDIGO solution scenario in Madrid

Concentration–response function	Age range	Estimated economic benefits (Millions €)
<i>Stafoggia et al.</i>	30–99	102.80
<i>Orellano et al.</i>	0–99	90.43

Table 156 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 40% INDIGO solution scenario in Madrid

For PM, the estimated economic benefits increase across the INDIGO scenarios, although the progression is not proportional to fleet replacement. The largest additional benefit occurs between the 20% and 30% scenarios, while the smaller increase at 40% suggests diminishing incremental gains within the configurations assessed. Stafoggia et al. consistently yields higher estimates than Orellano et al., but both functions show a similar progression across scenarios. This consistency supports the overall pattern of increasing benefits, while differences in their magnitude reflect the epidemiological assumptions and age groups covered by each function. As the same VSL is applied across the Madrid scenarios, the progression in monetised benefits directly reflects the underlying estimates of avoided premature mortality.

7.2.3.2. Nitrogen oxides (NO_x) results

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	15.16
<i>Kasdagli et al.</i>	0–99	17.36

Table 157 – Total monetised benefit all-cause mortality benefits per district associated with NO_x under the 10% INDIGO solution scenario in Madrid



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	27.48
<i>Kasdagli et al.</i>	0–99	31.43

Table 158 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 20% INDIGO solution scenario in Madrid

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	72.85
<i>Kasdagli et al.</i>	0–99	83.34

Table 159 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 30% INDIGO solution scenario in Madrid

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	85.73
<i>Kasdagli et al.</i>	0–99	98.06

Table 160 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 40% INDIGO solution scenario in Madrid

The NOx results indicate that the economic benefits depend on how effectively each INDIGO scenario reduces population exposure, rather than on fleet replacement alone. The marked increase between the 20% and 30% scenarios, followed by a more moderate gain at 40%, suggests that equal increments in fleet replacement do not deliver equivalent additional benefits. Kasdagli et al. consistently produces higher estimates than Stafoggia et al., although both functions show the same progression across scenarios. This agreement supports the consistency of the observed trend, while the differences in absolute values highlight the sensitivity of the economic assessment to the concentration–response function selected.

7.2.3.3. Overall assessment

For Madrid, the economic results under the 40% INDIGO scenario are summarised below as the minimum–maximum range of the estimates obtained from the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals.



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

Pollutant	Concentration-response function	Benefit range by pollutant (Million €)
PM	<i>Orellano et al.; Stafoggia et al.</i>	90-103
NOx	<i>Kasdagli et al.; Stafoggia et al.</i>	85-98

Table 161 – Range of estimated monetised all-cause mortality benefits by pollutant under the 40% INDIGO scenario in Madrid

7.2.4. Barcelona airport

7.2.4.1. Particulate matter (PM) results

<i>Concentration-response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>Stafoggia et al.</i>	30–99	16.62
<i>Orellano et al.</i>	0–99	14.73

Table 162 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 10% INDIGO scenario in Barcelona

<i>Concentration-response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>Stafoggia et al.</i>	30–99	18.51
<i>Orellano et al.</i>	0–99	16.42

Table 163 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 20% INDIGO scenario in Barcelona

<i>Concentration-response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>Stafoggia et al.</i>	30–99	18.62
<i>Orellano et al.</i>	0–99	16.50

Table 164 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 30% INDIGO solution scenario in Barcelona

<i>Concentration-response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>Stafoggia et al.</i>	30–99	19.21
<i>Orellano et al.</i>	0–99	17.04

Table 165 – Total monetised benefit all-cause mortality benefits per district associated with PM under the 40% INDIGO solution scenario in Barcelona.



INDIGO project has received funding from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055.

The PM-related economic assessment shows positive monetised mortality benefits across all INDIGO scenarios. Both concentration–response functions indicate a non-linear progression, with the largest additional gain occurring between Solutions 10% and 20%, followed by an almost negligible increase at 30% and a further moderate improvement at 40%. Most of the estimated benefit is therefore already achieved under the lowest replacement scenario.

Stafoggia et al. consistently produces higher estimates than Orellano et al., although both functions show the same scenario pattern. This consistency supports the interpretation that increasing fleet replacement delivers additional benefits, but their magnitude is not proportional to the share of INDIGO aircraft. The two sets of estimates should be interpreted separately, as alternative valuations of the same mortality endpoint.

7.2.4.2. Nitrogen oxides (NOx) results

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	1.8
<i>Kasdagli et al.</i>	0–99	2

Table 166 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 10% INDIGO scenario in Barcelona

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	1.85
<i>Kasdagli et al.</i>	0–99	2.11

Table 167 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 20% INDIGO scenario in Barcelona

Concentration–response function	Age range	Total monetised benefit (Million €)
<i>Stafoggia et al.</i>	30–99	1.87
<i>Kasdagli et al.</i>	0–99	2.14

Table 168 – Total monetised benefit all-cause mortality benefits per district associated with NOx under the 30% INDIGO scenario in Barcelona



<i>Concentration–response function</i>	<i>Age range</i>	<i>Total monetised benefit (Million €)</i>
<i>Stafoggia et al.</i>	30–99	1.95
<i>Orellano et al.</i>	0–99	2.23

Table 169 – Total monetised benefit all-cause mortality benefits per district associated with NO_x under the 40% INDIGO scenario in Barcelona

The economic assessment indicates positive monetised benefits associated with reductions in NO_x-related all-cause mortality in Barcelona. Both concentration–response functions show a gradual increase across the INDIGO scenarios, with the highest benefits obtained under the 40% configuration. However, most of the benefit is already achieved at Solution 10%, while subsequent increases generate comparatively modest additional gains. The progression is therefore non-linear, with the smallest improvement occurring between the 20% and 30% scenarios.

Kasdagli et al. consistently yields higher estimates than Stafoggia et al., reflecting differences in the epidemiological functions and the age groups considered. These estimates represent alternative valuations of the same health endpoint and should not be added together. Their consistent progression nevertheless supports a common interpretation of the scenario trend.

The monetary values should also be interpreted alongside the limited geographical coverage of the assessment. They refer to the population within Barcelona’s ten districts and exclude potential benefits in surrounding municipalities closer to the airport. Furthermore, the valuation translates small reductions in expected mortality into monetary terms through the adopted VSL; consequently, benefits expressed in millions do not imply a large number of avoided deaths.

7.2.4.3. Overall assessment

For Barcelona, the economic results under the 40% INDIGO scenario are summarised below as the minimum–maximum range of the estimates obtained from the concentration–response functions considered for each pollutant. These ranges reflect differences between function-specific estimates and do not represent statistical confidence intervals. PM-related monetised benefits are consistently higher than those associated with NO_x within the population and geographical boundaries considered.

Pollutant	Concentration-response function	Benefit range by pollutant (Million €)
PM	<i>Orellano et al.; Stafoggia et al.</i>	17-19
NO_x	<i>Kasdagli et al.; Stafoggia et al.</i>	1.95-2.23

Table 170 – Range of estimated monetized all-cause mortality benefits by pollutant under the 40% INDIGO scenario in Barcelona



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8. Conclusions and future work

General objectives and overall assessment

The main objective of this deliverable has been to assess the potential environmental, health and economic benefits associated with the introduction of the INDIGO aircraft concept into airport operations. To this end, the assessment has combined fast-time RAMS simulations, high- and low-fidelity environmental modelling, noise calculations, data-fusion and correction procedures, and health and economic impact methodologies. The analysis has been conducted for four representative airport use cases: Riga (RIX), Dortmund (DTM), Madrid (MAD) and Barcelona (BCN), considering a Reference scenario and four progressively increasing INDIGO introduction scenarios of 10%, 20%, 30% and 40%.

The results demonstrate that the INDIGO concept has the potential to reduce both local air-quality impacts and aircraft-noise exposure around airports. However, the magnitude of the improvement is strongly dependent on the airport configuration, traffic composition, population distribution, flight procedures and, particularly, on which conventional flights can effectively be replaced by INDIGO aircraft under the flyability and replaceability constraints. Consequently, the percentage of INDIGO aircraft introduced into the fleet cannot be directly interpreted as an equivalent percentage reduction in environmental or health impacts. The results show in several cases a non-linear response, with substantial benefits already obtained at intermediate replacement levels and smaller incremental improvements at higher replacement levels. This behaviour is consistent with the assumptions established for the progressive substitution of the conventional fleet.

Overall, the four case studies provide complementary evidence of the potential of INDIGO. Riga and Madrid show particularly strong reductions in aircraft-noise exposure, while the LAQ assessment demonstrates reductions across all pollutants considered in the four airports. Barcelona presents a different response, mainly because existing flight procedures already direct a substantial part of the traffic towards the Mediterranean Sea, limiting the additional noise benefit that can be achieved through aircraft replacement alone.

The assessment should nevertheless be interpreted within the modelling assumptions and limitations described in the deliverable. In particular, the INDIGO aircraft performance model calibrated for Riga is transferred to the other airports, the high-fidelity LAQ modelling is based on airborne trajectories, taxi emissions are represented through a more general approximation, and the health and economic assessment is limited to PM and NO_x.

Conclusions from LAQ and noise results

Riga Airport

Riga shows a consistent improvement in local air quality under all INDIGO scenarios. Under SOL40, the average reductions relative to the Reference scenario reach **49.34% for CO**, **50.28% for HC**, **20.15% for daily mean NO_x**, **16.08% for maximum hourly NO_x**, **19.61% for PM** and **28.74% for BC**. Thus, the largest reductions are obtained for HC and CO, while PM and NO_x show more moderate but still consistent improvements.

The spatial results also show a clear reduction in the extent and intensity of the main concentration areas. In the Reference scenario, CO concentrations reach approximately **7 µg/m³**, while HC presents local maximums of around **5 µg/m³**. Under SOL40, the number



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and extent of the most pronounced peaks are reduced. BC remains locally concentrated around the airport infrastructure, although its overall spatial extent decreases.

The noise results are particularly pronounced. The population exposed to more than **55 dBA LDEN** decreases from **2340 inhabitants in the Reference scenario to 510 under SOL40**, corresponding to a **78% reduction**. The reduction is already 66% under SOL30, showing that a substantial part of the noise benefit is obtained before reaching the maximum replacement considered.

Riga therefore illustrates a case in which INDIGO provides simultaneous improvements in LAQ and noise, with the acoustic benefit being particularly strong for the population exposed to the highest noise levels.

Dortmund Airport

Dortmund also presents reductions across all LAQ indicators. Under SOL40, the average reduction reaches **52.69% for CO, 52.70% for HC, 29.40% for daily mean NOx, 39.22% for maximum hourly NOx, 32.99% for PM and 33.14% for BC**. CO and HC are again the pollutants showing the largest reductions, whereas NOx, PM and BC show more moderate improvements.

The noise results show an especially strong relative reduction. The population exposed to more than **55 dBA LDEN** decreases from **9372 to 2201 inhabitants**, representing a **77% reduction** under SOL40. Even SOL10 produces a 59% reduction. The main particularity of Dortmund is the spatial distribution of the affected population: rather than one large continuous urban area, the exposed population is distributed among several municipalities and settlements along the flight paths. Therefore, the benefit consists mainly of reducing exposure across several dispersed population concentrations.

This characteristic is also reflected in the health-related noise indicators. Under SOL40, the population above 45 dBA LDEN is reduced by 35%, the population above 40 dBA Night by 61%, annoyance by 54%, and highly sleep-disturbed population by 74%. The particularly strong night-time improvement is related to the relatively limited number of night operations at Dortmund, meaning that the remaining night-time exposure is concentrated in a more restricted area.

Madrid Airport

Madrid presents some of the strongest LAQ improvements among the four case studies. Under SOL40, the average reductions reach **59.66% for CO, 64.96% for HC, 37.95% for daily mean NOx, 36.06% for maximum hourly NOx, 44.84% for PM and 45.42% for BC**. HC therefore represents the largest reduction, followed by CO, while PM and BC are reduced by approximately 45%.

The spatial analysis confirms a substantial reduction in the extent of the pollutant concentration areas. For example, the reference PM concentrations reach approximately **1–3 µg/m³** in several areas west and south of the airport, whereas under SOL40 the remaining elevated concentrations become considerably more localized. The reduction in maximum hourly NOx is somewhat lower than that of the daily mean, illustrating that replacing aircraft can substantially reduce overall exposure without necessarily eliminating the individual peak concentrations generated by specific operations.



The acoustic improvement is particularly significant. The population exposed to more than **55 dBA LDEN** decreases from **60423 inhabitants in the Reference scenario to 11471 under SOL40**, representing an **81% reduction**. The largest spatial improvements are observed around the western side of the airport, particularly the Barajas and Alameda de Osuna areas.

At the health-oriented noise thresholds, SOL40 reduces the population above 45 dBA LDEN by 31%, the population above 40 dBA Lnight by 49%, annoyance by 31% and highly sleep-disturbed population by 49%.

Barcelona Airport

Barcelona presents a different environmental response. The LAQ results nevertheless show reductions for every pollutant assessed. Under SOL40, the reductions are **35.75% for CO**, **66.44% for HC**, **53.27% for daily mean NOx**, **8.99% for maximum hourly NOx**, **60.07% for PM** and **61.14% for BC**. HC, BC and PM therefore show the largest reductions, all above 60%, while the maximum hourly NOx indicator shows a considerably smaller reduction.

This difference between daily-average and peak NOx behaviour is relevant: the daily mean concentration can be substantially reduced even when the particular operation responsible for the maximum hourly concentration is not replaced by an INDIGO aircraft. The document therefore identifies the selection of flights, taxi distances and phase-specific emission rates as aspects requiring further analysis for Barcelona.

The noise results are positive but more moderate than for the other airports. The population exposed to more than **55 dBA LDEN** decreases from **87101 to 48144 inhabitants**, corresponding to a **45% reduction** under SOL40. The comparatively smaller reduction is explained by the existing operational configuration, which already directs aircraft towards the Mediterranean Sea and therefore limits exposure of densely populated areas. Consequently, INDIGO mainly reduces the intensity of the existing noise footprint rather than substantially changing its geographical configuration.

The same behaviour is observed in the health-oriented noise indicators: the population above 45 dBA LDEN decreases by 17%, while the population above 40 dBA Lnight and the highly sleep-disturbed population decrease by 9%. This limited night-time improvement is consistent with the preferential use of runway configurations that already direct aircraft towards the sea.

Health and economic impact conclusions

The health assessment extends the environmental results by estimating the potential population-level consequences of the changes in PM and NOx exposure. These results represent the **incremental health effect of the INDIGO scenarios relative to the Reference scenario**, rather than the total mortality burden attributable to airport-related air pollution. The assessment combines modelled concentration changes, population, baseline mortality and selected concentration–response functions.

Riga airport

Riga presents substantial modelled health benefits under SOL40. The estimated avoided all-cause mortality associated with PM ranges from **83 to 189 deaths**, depending on the concentration–response function, while the corresponding NOx estimate ranges from **39 to 45 deaths**. These values should be considered separately and should not be added together.



The economic assessment translates these mortality-related benefits into monetary values using the Value of a Statistical Life. Under SOL40, the estimated PM-related benefit ranges from approximately **€361 million to €820 million**, while the NO_x-related benefit ranges from approximately **€172 million to €196 million**. The wide PM range reflects the differences between the epidemiological functions used.

The Riga case therefore provides a strong illustration of how reductions in local pollutant concentrations can propagate through the assessment chain from environmental improvement to estimated health and economic benefits.

Dortmund airport

Dortmund shows smaller absolute health effects than Riga, Madrid or Barcelona mainly because of its smaller population and lower level of airport activity. Nevertheless, the direction of the effect is consistently positive across the scenarios.

Under SOL40, the estimated avoided all-cause mortality ranges from **4–10 deaths for PM** and **10–11 deaths for NO_x**. The NO_x-related estimates increase relatively progressively with INDIGO introduction, while the PM results show a more pronounced increase between the intermediate scenarios.

The associated economic benefits under SOL40 are estimated at approximately **€33–75 million for PM** and **€50–57 million for NO_x**. The PM estimates are particularly sensitive to the selected concentration–response function, while the NO_x estimates show a narrower range.

The Dortmund case is therefore particularly useful for demonstrating that the magnitude of the health and economic effect depends not only on the percentage of INDIGO aircraft but also on the population exposed and the spatial distribution of the concentration reductions.

Madrid airport

Under SOL40, the estimated avoided all-cause mortality ranges from **86–94 deaths for PM** and **85–100 deaths for NO_x**. Both pollutants therefore show benefits of a similar order of magnitude, although the NO_x estimates display greater variation between the selected concentration–response functions.

The corresponding economic assessment estimates PM-related benefits of approximately **€90–103 million** and NO_x-related benefits of approximately **€86–98 million** under SOL40. As in the other airports, these values represent alternative estimates associated with different epidemiological functions rather than quantities that should be added together.

An important limitation for Madrid is that the So and Andersen concentration–response function could not be applied because compatible baseline mortality data were not available. Consequently, the PM-related cardiovascular mortality endpoint associated exclusively with that function could not be quantified. This represents a data-compatibility limitation rather than evidence that the corresponding health effect is absent.

Barcelona airport

Under SOL40, the estimated avoided all-cause mortality associated with PM is **5–6 deaths**, while the NO_x estimate remains **below one expected avoided death**. The assessment is restricted to Barcelona's ten administrative districts and does not include neighbouring



municipalities closer to the airport, which is particularly important given the airport's location outside the city boundaries.

The economic results are consistent with this limited geographical scope. Under SOL40, PM-related monetised benefits are estimated at approximately **€17–19 million**, while NO_x-related benefits range from **€1.95–2.23 million**. The values should be interpreted as monetary representations of small changes in expected mortality risk within the population included in the analysis and should not be interpreted as a direct monetary value assigned to individual lives.

The Barcelona case therefore highlights an important point for the interpretation of the four use cases: a comparatively lower estimated health or economic benefit does not necessarily indicate a weaker aircraft-level environmental performance. It can instead result from the interaction between the magnitude and spatial distribution of the concentration reduction, the population included in the assessment and the existing operational configuration.

Overall conclusions on the contribution and future potential of INDIGO

Taken together, the four use cases demonstrate the potential of the INDIGO concept to generate simultaneous improvements in local air quality, aircraft-noise exposure and the associated population-level health impacts.

From an LAQ perspective, all four airports show reductions for every pollutant considered under SOL40. The magnitude and pollutant sensitivity vary by airport: Riga and Dortmund show their strongest improvements for CO and HC; Madrid combines particularly strong reductions in HC and CO with substantial reductions in PM and BC; and Barcelona shows particularly strong reductions in HC, PM and BC. The results also confirm that daily-average indicators generally show a stronger response than individual peak indicators, particularly for NO_x.

The noise assessment provides a particularly clear demonstration of the potential benefit of INDIGO. Under SOL40, the population exposed to levels above 55 dBA LDEN is reduced by 78% in Riga, 77% in Dortmund, 81% in Madrid and 45% in Barcelona. These results show that aircraft replacement can significantly reduce the intensity of existing noise footprints, although the magnitude of the benefit is highly dependent on the airport's flight paths, night operations and surrounding population distribution.

The health and economic assessments further demonstrate that environmental improvements can translate into measurable population-level benefits. The magnitude of these benefits varies substantially between airports because it depends on both the environmental improvement and the number and characteristics of people exposed to it. Riga and Madrid, in particular, illustrate the potential for substantial health and economic benefits when significant pollutant reductions coincide with large exposed populations.

An important overall finding is that the benefits do not increase linearly with INDIGO introduction. In several cases, a large proportion of the total improvement is already achieved at 20% or 30% replacement, while the additional benefit between 30% and 40% is comparatively smaller. This confirms that the environmental value of INDIGO depends not only on the number of aircraft replaced but also on **which aircraft and operations are replaced** and where their emissions and noise are experienced. The replacement strategy should therefore evolve from a simple fleet-share approach towards an exposure- and impact-oriented allocation of INDIGO operations.



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The four airports also demonstrate the transferability of the INDIGO assessment framework across substantially different operational and demographic environments. At the same time, the differences observed between Riga, Dortmund, Madrid and Barcelona show that future applications should increasingly incorporate airport-specific operational characteristics rather than relying on a common representation of the aircraft and its environmental performance.

Overall, the results provide evidence that INDIGO has significant potential as part of a broader strategy for reducing the environmental footprint of airport operations. The results should, however, be understood as modelled potential under the scenarios assessed rather than as a prediction of the environmental performance that would necessarily be achieved in operational deployment.

Recommended future work

The following activities would further strengthen the assessment and facilitate the transition from the current scenario-based evaluation towards a more operationally representative assessment:

1. **Expand the traffic samples and test the robustness of the results.**

The current use of representative one-week or one-day traffic windows should be complemented with multiple representative periods covering different traffic intensities, seasonal conditions and operational configurations. This would allow the sensitivity of the environmental benefits to the selected traffic sample to be quantified.

2. **Develop airport-specific INDIGO replacement strategies.**

The present scenarios are primarily defined through prescribed INDIGO introduction levels. Future work should investigate whether selecting INDIGO flights according to their environmental impact could generate greater reductions than a simple percentage-based replacement. Although the current strategy already consider criteria such as conventional aircraft type/emissions, noise contribution, flight phase, trajectory, other factors could be included such as population exposure and time of operation and not limited to a specific percentage of replacement but applying to all feasible candidates.

3. **Improve the representation of taxi and ground operations.**

Taxiing is particularly relevant for NO_x and other local pollutants. A more detailed representation of taxi distances, taxi times, engine operating conditions and airport-specific ground movements would reduce uncertainty and help explain differences such as the lower reduction observed for some peak NO_x indicators.

4. **Extend high-fidelity validation beyond Riga.**

The current methodology assumes transferability of the INDIGO aircraft performance model and correction factors from Riga to the other airports. Future work should validate the environmental model under airport-specific meteorological, operational and traffic conditions and, where feasible, develop airport-specific correction factors.



5. Increase the temporal and meteorological resolution of the LAQ assessment.

Further simulations using a wider range of wind conditions, atmospheric stability classes and representative meteorological situations would help determine the robustness of the spatial concentration patterns and avoid over-reliance on a limited set of atmospheric conditions.

6. Improve the health assessment geographical scope.

The Barcelona results particularly demonstrate the importance of defining the study population according to the airport's actual area of influence rather than administrative boundaries alone. Future assessments should consider neighbouring municipalities and, where possible, use a common geographical framework covering the complete population potentially exposed to airport-related pollutant changes.

7. Improve the treatment of peak exposure indicators.

The differences observed between daily mean and maximum hourly NO_x reductions demonstrate the importance of identifying the individual operations responsible for concentration peaks. Future work should explicitly track these operations and determine whether targeted INDIGO replacement could provide greater reductions in short-term exposure.

8. Extend the economic assessment beyond mortality-related LAQ benefits where sufficiently robust evidence is available.

The current economic assessment focuses on mortality-related benefits associated with PM and NO_x. Future work could investigate additional health endpoints and, if supported by sufficiently mature evidence, other economic consequences of reduced noise and air pollution exposure.

9. Assess higher-level deployment scenarios.

The current 40% scenario is considered the highest realistic replacement level within the deliverable. Future studies could nevertheless explore longer-term fleet-transition pathways, including the conditions under which higher INDIGO replacement could become operationally feasible, and identify how environmental benefits evolve as the conventional fleet progressively decreases.

10. Integrate environmental assessment with a life-cycle perspective.

The present assessment focuses on local operational impacts around airports. A future stage could complement this analysis with life-cycle assessment of aircraft production, batteries, energy supply, maintenance and end-of-life processes to determine how local operational benefits relate to the broader environmental performance of the INDIGO concept.

These activities would allow the INDIGO environmental assessment to evolve from the current demonstration of potential benefits towards a more comprehensive decision-support framework capable of identifying **where, when and under which operational conditions INDIGO aircraft can deliver the greatest environmental and societal benefit.**



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