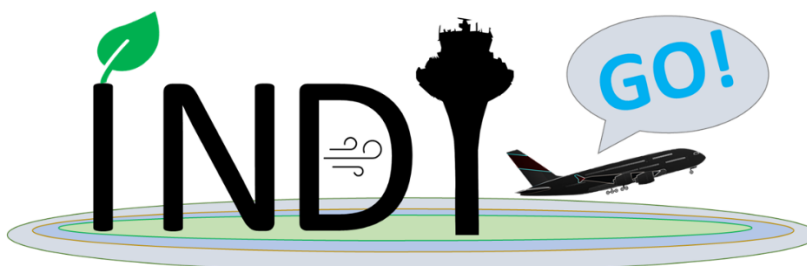


RESEARCH PROJECT MANAGEMENT

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Deliverable 6.1: Improved model for evaluating pollutants propagation from data fusion

Project: 101096055

INtegration and Digital demonstration of low-emission

aIrcraft technoloGies and airport Operations

INDIGO

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

Deliverable D6.1



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Contents

List of acronyms	6
1 Introduction.....	7
2 Description of the generation of the trajectories	8
2.1 Flight Selection	8
2.2 Trajectory Generation	9
2.3 Configuration in RAMS Plus	11
3 Description of the emission rates calculation	15
4 Description of the low-fidelity model and simulations.....	17
4.1 Outputs from the model	17
4.2 Pollutant concentrations calculation (PC)	17
4.3 Pollutant dispersion (PD)	20
5 Description of the high-fidelity model and simulations.....	21
5.1 Hypotheses	21
5.2 Governing equations and numerical set-up	23
5.3 Initial conditions.....	24
5.4 Boundary conditions	28
6 Comparison of the high- and low-fidelity simulations.....	33
7 Algorithms for data fusion	35
7.1 Parameter Space Definition	36
7.2 Data pre-processing and generation of ROM	38
7.3 Estimation of ROM error	39
8 Application of the data fusion to the low-fidelity simulations and assessment of the improvement of pollutants predictions	43
9 References	49



List of figures

Figure 1 - Representation of Riga International Airport (EVRA) as encoded in RAMS Plus, showing the runway (orange) and the airport ground movement network (blue) used for the simulation of aircraft taxi operations.	12
Figure 2 - SID and STAR implementation in RAMS Plus for Riga Airport, reproducing the procedural structure derived from the AIP and radar-based reconstruction.	13
Figure 3 - Example of input file for high-fidelity simulations.	14
Figure 4 - Example of Input file for AERMOD.	14
Figure 5. Block diagram with the inputs and outputs for gas turbine and combustion chamber surrogate. Reproduced from deliverable D3.2.	15
Figure 6 - Example of trajectories generated by RAMS at Riga's airport.	18
Figure 7 - Example of trajectories converted into segments at Riga's airport.	18
Figure 8 - Example of a PLT output file.	19
Figure 9 - Example of dispersion of CO over Riga at different simulation times measured at 1.5-meter height.	20
Figure 10 - Pollutant share between phases for the conventional aircraft trajectories.	22
Figure 11 - 3D view of the wing-tip vortices.	25
Figure 12 - 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.	26
Figure 13 - Velocity magnitude field (in m/s) for the turbulent boundary layer from the precursor simulation. Top: slice parallel to the mean wind direction and perpendicular to the ground. Bottom: slice parallel to the ground at 40 m height.	27
Figure 14 - Sketch of the procedure to map the velocity field from the precursor simulation to the nearby airport region in the zone unperturbed by the aircraft.	28
Figure 15 - Sketch of the procedure for the generation of the turbulent inlet boundary conditions.	29
Figure 16 - Velocity magnitude initial field for a horizontal slice at 40 m height. The perturbation of the aircraft in the field is observed close to the bottom side. Scale is saturated to improve the visualization of the structures of the flow.	30
Figure 17 - Velocity magnitude initial field for a vertical slice parallel to the trajectory. The plane cuts part of the vortices created by the aircraft. Scale is saturated to improve the visualization of the structures of the flow.	30
Figure 18 - Snapshots for the velocity magnitude for inlet boundary conditions. Scale is saturated to improve the visualization of the structures of the flow.	31
Figure 19 - Representation of velocity magnitude in m/s (left) and the CO mass fraction (right) in vertical slices normal to the trajectory over time.	31
Figure 20 - 3D views of the dispersion, convection and mixing of the pollutant plumes left by the aircraft. For visualization purposes only the inlet lateral faces are shown. An isosurface of the velocity magnitude is included to illustrate the flow structures (grey layer at the bottom). Green arrow in each of the figures indicate the direction of wind. Black arrows indicate the direction in which time advances.	32
Figure 21 - Comparison of high (top row) and low fidelity (bottom row) simulations for different pollutants at a height of 1.5 m. Solutions for the landing of the solution aircraft after 2400 s after the end of the trajectory. Wind velocity of 1.54 m/s (10 m height) and wind direction of 270°.	33
Figure 22 - Comparison of high (top row) and low fidelity (bottom row) simulations for different pollutants at a height of 1.5 m. Solutions for the take-off of the solution aircraft after 1500 s after the end of the trajectory. Wind velocity of 1.54 m/s (10 m height) and wind direction of 210°.	34
Figure 23 - Parameter space and snapshot distribution for INDIGO case. Planar projections shown on right. The LTO phase and runway are indicated here but the data is considered together.	37



Figure 24 - Parameter space and snapshot distribution for conventional case. Planar projections shown on right. The LTO phase and runway are indicated here. Landing and take-off cases are treated separately when generating the ROM.	38
Figure 25. An example of aggregate CO concentrations for LES and AERMOD as well as their difference. The operation to obtain the latter is also illustrated.	39
Figure 26. Leave-one-out error of CO concentrations based on ROM predictions for the INDIGO aircraft.	40
Figure 27. Leave-one-out error of CO concentrations based on ROM predictions for the conventional aircraft; landing only.	40
Figure 28. Leave-one-out error of CO concentrations based on ROM predictions for the conventional aircraft; take-off only.	41
Figure 29. Demonstrative example of qualitative error analysis for ROM model of the INDIGO aircraft. The yellow bands mark the interval at which the confidence level is ascertained.	42
Figure 30. Deltas calculated at RIX for each pollutant and receptor.	44
Figure 31. Deltas calculated at Dortmund (DTM) for each pollutant and receptor.	45
Figure 32. Deltas calculated at Madrid-Barajas (MAD) for each pollutant and receptor.	46
Figure 33. Deltas calculated at Barcelona-El Prat (BCN) for each pollutant and receptor.	47
Figure 34. Comparison between initial resulted concentrations of CO ($\mu\text{g}/\text{m}^3$) (left) and concentrations after deltas application (right) at RIX.	48



List of acronyms

ADS-B	Automatic Dependent Surveillance Broadcast
AERMIC	American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee
AGL	Above Ground Level
AIP	Aeronautical Information Publication
DHEP	Distributed Hybrid Electric Propulsion
EPA	Environmental Protection Agency
EVRA	Riga International Airport
KPI	Key Performance Indicator
LAQ(N)	Local Air Quality (and Noise)
LARW	Large Aspect Ratio Wings
LES	Large Eddy Simulation
MDO	Multidisciplinary Design and Optimization
PC	Pollutant Concentrations
PD	Pollutant Dispersion
PM	Particulate Matter
POD	Proper Orthogonal Decomposition
PSFC	Power Specific Fuel Consumption
RANS	Reynolds Averaged Navier-Stokes
RBF	Radial Basis Function
RF	Radius-to-Fix
RNP AR	Required Navigation Performance Authorization Required
ROM	Reduced Order Model
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival
TMA	Terminal Manoeuvring Area
UC	Use Case
UHC	Unburnt Hydrocarbons
UTC	Coordinated Universal Time



1 Introduction

INDIGO is a European project framed in the Horizon Europe programme (grant agreement No. 101096055) which aims at progressing towards net-zero aviation by innovating the design and the near-airport operations of the mid-range aircraft class. To this end, DHEP (Distributed Hybrid Electric Propulsion) and LARW (Large Aspect Ratio Wings) technologies have been thoroughly investigated as key potential solutions to drastically reduce acoustic and emissions contamination. In particular, two of the backbone objectives of the project were, on the one hand, exploring the margins of improvement of the LAQ (Local Air Quality) related to the combined use of DHEP and LARW and, on the other hand, enhancing the predictive capabilities of the current methods used to evaluate pollutants maps in the airport areas in order to provide more accurate predictions of the LAQ and better inform policy-makers and air navigation services providers. As explained in the following, different tasks were developed in the frame of WP6 'LAQN improvement from DHEP-LARW technology development' to cover previous goals.

To this end, high-fidelity simulations were performed for a series of representative flights in order to provide accurate maps of pollutants generated by aircraft operation. Such data was computed for both conventional and solution aircrafts, being the last one designed from the optimized application of DHEP and LARW as part of the output from WP2 'Performance and noise model of distributed hybrid electric propulsion' and WP3 'Models and simulations for airframe and propulsion integration' together with WP5 'Airframe-propulsion optimal integration under uncertainty'. Trajectories were defined in WP4 'Models for airport LAQN performance and operations'. Similarly and in parallel to the high-fidelity simulations, low-fidelity simulations were carried out for the same flights and conditions.

The comparison of both sets of simulations allowed to devise a model (data fusion) which can correct the low-fidelity simulations in order to provide more trustable predictions of the airport operation. The results of these activities are gathered in the present document while the quantification of the improvement of the solution aircraft in terms of LAQN will be analysed in deliverable D6.2.



2 Description of the generation of the trajectories

The generation of realistic aircraft trajectories represents one of the core methodological steps of the simulation workflow developed within the INDIGO project, as it directly determines the fidelity with which gate-to-gate operations are reproduced by the code RAMS Plus (RAMS, 2026). Across all case studies, this process follows a consistent logical structure, articulated in three main phases: the selection of a representative and operationally reliable traffic sample, the reconstruction of lateral and vertical flight profiles from available data sources, and the translation of these profiles into the input format required by the simulation engine.

While the underlying methodology is common to all airports considered in the project, its practical implementation varies according to the type and granularity of data available at each site. Larger airports, supported by institutional repositories and detailed operational records, allow a more direct reconstruction of real trajectories, whereas smaller airports often require complementary strategies, combining open-source data, aeronautical publications, and, when possible, empirical surveillance data, to achieve an equivalent level of realism. This adaptability constitutes one of the strengths of the proposed approach, as it enables the same conceptual framework to be applied consistently across heterogeneous operational contexts.

The following section illustrates this methodology of trajectory generation for data fusion tasks with reference to Riga International Airport (EVRA), selected as the reference airport for the project in which flight selection and trajectory reconstruction could be based directly on empirical radar data, offering a high-fidelity example of the overall process.

2.1 Flight Selection

The week from the 21st to the 27th of August of 2023 was identified as the typical week for RIX traffic representativeness, thus this period was finally chosen for flight selection. For the global LAQN benefits assessment (presented in deliverable D6.2 of this project), the whole week data is considered. However, for the data fusion task, only some representative time slots from this week were selected.

The time slots were established by selecting eight hourly time slots—comprising four peak and four off-peak hours—across the summer week of August 21–27, 2023. This yielded an initial dataset spanning August 21–25, 2023, containing 128 flights. Following data cleaning and processing, 125 flights were retained for the selection while three flights were excluded due to the lack of representative historical



Standard Instrument Departure (SID) or Standard Terminal Arrival (STAR) procedure patterns.

The breakdown of selected time slots from the RIX traffic dataset is detailed in Table 1.

Table 1 - Time slots taken from RIX traffic dataset.

Date	Hour	Arrivals	Departures
21/08/2023	07:00-08:00	0	20
21/08/2023	12:00-13:00	4	4
21/08/2023	17:00-18:00	5	12
21/08/2023	22:00-23:00	23	0
22/08/2023	07:00-08:00	0	20
23/08/2023	18:00-19:00	4	8
24/08/2023	22:00-23:00	19	2
25/08/2023	19:00-20:00	3	4

Eventually, a subset of 44 flights were selected from the 125 flights, since they were the unique combination of aircraft type, operational procedure, and vertical profile type (climb or descent), as all other flights within this set are repetitive profiles. This final selection comprises of 31 conventional aircraft and 13 INDIGO aircraft, which will be the input trajectories for low and high-fidelity simulations explained in the following sections.

2.2 Trajectory Generation

The availability of complete radar tracks for Riga allowed a direct and high-fidelity reconstruction of both lateral trajectories and vertical profiles.

The generation process first involved the extraction of kinematic parameters (ground speed and vertical speed) at predefined altitude intervals, computing their mean values in order to obtain smoothed climb and descent profiles, representative of the aggregate behaviour of the fleet rather than of individual stochastic realisations. In parallel, ground tracks were aggregated to obtain a representative mean lateral trajectory, capable of summarising the dominant routing patterns actually observed in real operations.

The construction of the traffic scenario for EVRA relied on a bottom-up approach, based on the availability of real operational data provided directly by airport personnel. This setup allowed privileged access to detailed radar tracks and complete procedural information, covering both departures and arrivals.



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The flight selection process followed the general filtering criteria already described for the overall INDIGO Project dataset, applied specifically to the Riga context. Trajectories corresponding to missed approaches, incomplete ADS-B (Automatic Dependent Surveillance Broadcast) tracks, or unrealistic positional jumps were excluded. Altitude validation was also carried out, retaining only tracks between airport elevation and 3500 ft AGL (Above Ground Level), in order to preserve consistency of vertical profiles within the Terminal Manoeuvring Area (TMA). Further checks concerned vertical speed, excluding flights with rates exceeding 5000 ft/min, and time normalisation of all timestamps into a uniform UTC format.

Given the bidirectional nature of Riga's runway 18/36, flights were analysed separately according to the runway in use, to capture the operational asymmetry determined by prevailing wind conditions and traffic distribution. Departures were further classified into three main procedural categories, consistent with the structure published in the AIP (Aeronautical Information Publication) Latvia: group "F", corresponding to southbound routes; group "H", relating to northbound routes; and group "J", also directed northbound but characterised by an early turn towards the west. For each group, both directional variants (eastbound and westbound) were considered, so as to faithfully represent the operational behaviour observed in the radar data.

For departures, the reconstruction relied directly on the empirical radar tracks recorded for each of the three procedural groups previously identified (F, H, and J), aggregated separately for their eastbound and westbound variants. This approach ensured that the resulting lateral profiles faithfully reproduced the dispersion of initial climb-out paths and their progressive convergence towards the published route structure, as actually observed in real operations, rather than relying solely on the nominal AIP geometry.

Regarding arrivals, although Riga features RNP AR (Required Navigation Performance Authorization Required) procedures, their use is however restricted to a single operator equipped with the specific avionics capabilities required (including RF, Radius-to-Fix, turns), the reconstruction of landing trajectories relied primarily on the STAR procedures published in the AIP and on the subsequent conventional "T-bar" ILS approaches, the latter representative of the vast majority of commercial operations. This methodological choice ensured that the simulated profiles reflected the actual operations of the airport during the reference period, rather than theoretical configurations of rare application.

Although radar tracks are used as the basis for the RAMS simulation, a set of operational criteria has been introduced to ensure that the analysis represents real-world operations as closely as possible while maintaining the use of representative trajectories.



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The following assumptions have been applied:

- A minimum gate occupancy time of 30 minutes has been established for each aircraft.
- A minimum separation of 5 minutes has been applied between consecutive aircraft assigned to the same STAR in order to avoid potential conflicts.

2.3 Configuration in RAMS Plus

Once the mean lateral and vertical profiles were reconstructed and validated, the subsequent step concerned their translation into the data format required by RAMS Plus. The translation of the reconstructed traffic and procedural data into the RAMS Plus simulation environment follows a structured, multi-step configuration process. The implementation workflow can be summarized in four main stages:

1. **Infrastructure encoding.** The airport layout, runway, taxiway network, apron, and stand configuration, is translated into the network-based structure required by RAMS Plus, consisting of geo-referenced ground nodes (GNodes) and directional links. This information populates the corresponding configuration files (navaid.dat, runway.dat, groundlink.dat, stand.dat), providing the geometric foundation upon which all aircraft movements are simulated.



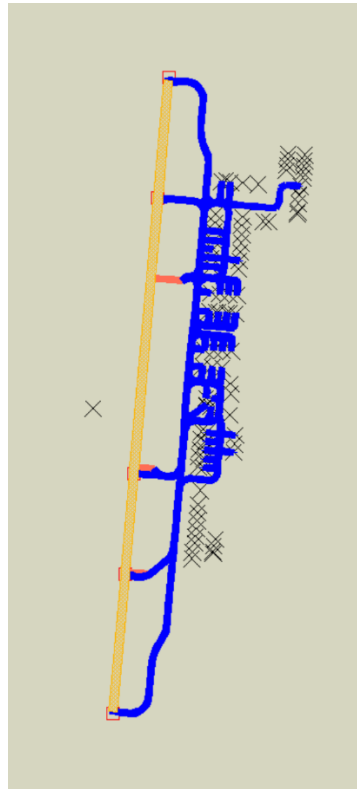


Figure 1 - Representation of Riga International Airport (EVRA) as encoded in RAMS Plus, showing the runway (orange) and the airport ground movement network (blue) used for the simulation of aircraft taxi operations.

2. **Procedure integration.** Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs), together with the associated approach procedures, are encoded as ordered sequences of navigation fixes linked to specific runways. These are stored in the `departureroute.dat` and `approachroute.dat` files, ensuring that each simulated flight is routed according to procedurally consistent lateral paths.



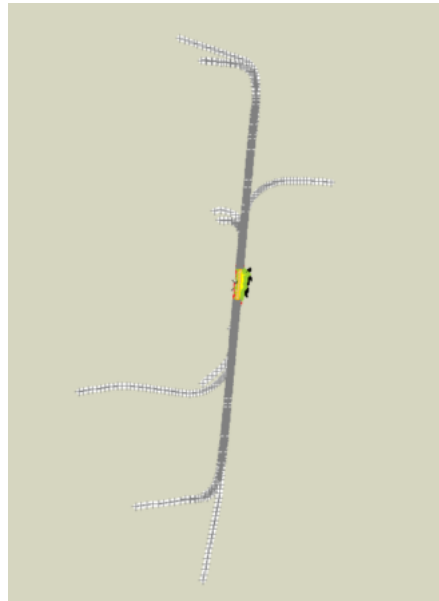


Figure 2 - SID and STAR implementation in RAMS Plus for Riga Airport, reproducing the procedural structure derived from the AIP and radar-based reconstruction.

3. **Ground movement modelling.** Depending on data availability, ground movements are represented either through routes automatically computed by the RAMS Plus simulation engine on the basis of network topology and stand assignment logic, or through taxi paths directly derived from empirical surveillance data, when available. In both cases, the resulting ground trajectories remain fully consistent with the underlying network configuration and reproduce the operational routing patterns characteristic of each airport.
4. **Flight plan population.** Traffic data are imported through two complementary files: `traffic.dat`, which defines the strategic attributes of each flight (identity, schedule, aircraft type, runway assignment), and `trafficprofile.dat`, which specifies the operational sequence of events, gate, SID/STAR, navigation fixes, runway, governing the 4D evolution of each flight within the simulation.

Once these elements are configured, RAMS Plus reconstructs the complete gate-to-gate trajectory of each flight, integrating airspace, ground, and procedural information into a coherent operational model. This modular implementation approach allows the same methodology to be consistently applied across different airports, regardless of the specific data sources employed for infrastructure reconstruction or ground movement characterization, thereby ensuring replicability of the workflow within the broader INDIGO simulation framework.



The simulated trajectories serve as key input for downstream models. In particular, the flightevent.out.1 file records simulated trajectories, detailing parameters such as 4D trajectory points (latitude, longitude, altitude), time, speed, and aircraft attitude. This data is then post-processed to construct individual trajectory segments, enabling the calculation of pollutant dispersion for each targeted pollutant. The resulting segmented-trajectory file (Figure 3) serves as an input for high-fidelity simulations (section 5) to derive INDIGO performance parameters and are also converted into standardized formats tailored for integration into low-fidelity models as AERMOD (Figure 4).

phase	procedure	Ni_cco_cdo_nev	aircraft	Attitude	speed_NM	h	track	time	lat	lng	modo_c	feet	lat2	lng2	modo_c2	fevz_ft_min	ENGINE_ID	NUMBER_OF_CO	rate_Kg_s	HC_rate_Kg_s	PM10rate	rate
TO	VALEDF	1	A319	TaxiOut	15	14:25:26	56.9223071	23.974987	0	14:25:30	56.92321	23.9749708	0	14:25:34	56.9235092	23.9750313	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:30	56.92321	23.9749708	0	14:25:34	56.9235092	23.9750313	0	14:25:39	56.9238069	23.9751127	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:34	56.9235092	23.9750313	0	14:25:39	56.9238069	23.9751127	0	14:25:43	56.9241046	23.9751945	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:39	56.9238069	23.9751127	0	14:25:43	56.9241046	23.9751945	0	14:25:47	56.9244032	23.9752645	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:43	56.9241046	23.9751945	0	14:25:47	56.9244032	23.9752645	0	14:25:52	56.924703	23.9753136	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:47	56.9244032	23.9752645	0	14:25:52	56.924703	23.9753136	0	14:25:56	56.9250029	23.9753626	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:52	56.924703	23.9753136	0	14:25:56	56.9250029	23.9753626	0	14:26:00	56.9253027	23.9754116	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:25:56	56.9250029	23.9753626	0	14:26:00	56.9253027	23.9754116	0	14:26:05	56.9256026	23.9754606	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:00	56.9253027	23.9754116	0	14:26:05	56.9256026	23.9754606	0	14:26:09	56.9259024	23.9755295	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:05	56.9256026	23.9754606	0	14:26:09	56.9259024	23.9755295	0	14:26:13	56.9262022	23.9755985	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:09	56.9259024	23.9755295	0	14:26:13	56.9262022	23.9755985	0	14:26:18	56.9265021	23.9756675	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:13	56.9262022	23.9755985	0	14:26:18	56.9265021	23.9756675	0	14:26:22	56.9268019	23.9756365	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:18	56.9265021	23.9756675	0	14:26:22	56.9268019	23.9756365	0	14:26:26	56.9271018	23.9757055	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:22	56.9268019	23.9756365	0	14:26:26	56.9271018	23.9757055	0	14:26:31	56.9274016	23.9757545	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:26	56.9271018	23.9757055	0	14:26:31	56.9274016	23.9757545	0	14:26:35	56.9277015	23.9758035	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:31	56.9274016	23.9757545	0	14:26:35	56.9277015	23.9758035	0	14:26:39	56.9280013	23.9758524	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:35	56.9277015	23.9758035	0	14:26:39	56.9280013	23.9758524	0	14:26:44	56.9283012	23.9759014	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:39	56.9280013	23.9758524	0	14:26:44	56.9283012	23.9759014	0	14:26:48	56.928601	23.9759504	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:44	56.9283012	23.9759014	0	14:26:48	56.928601	23.9759504	0	14:26:52	56.9289008	23.9759994	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:48	56.928601	23.9759504	0	14:26:52	56.9289008	23.9759994	0	14:26:57	56.9292007	23.9760479	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:52	56.9289008	23.9759994	0	14:26:57	56.9292007	23.9760479	0	14:27:01	56.9295005	23.9760974	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:26:57	56.9292007	23.9760479	0	14:27:01	56.9295005	23.9760974	0	14:27:05	56.9298004	23.9761465	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:27:01	56.9295005	23.9760974	0	14:27:05	56.9298004	23.9761465	0	14:27:10	56.9301002	23.9761955	0	0	0.00282	0.0005828	8.75E-06	
TO	VALEDF	1	A319	TaxiOut	15	14:27:05	56.9298004	23.9761465	0	14:27:10	56.9301002	23.9761955	0									

Figure 3 - Example of input file for high-fidelity simulations.

adept	ades	aircraft	wake	numberOfEn	procedure	Ni	runway	phase	stand	alt	groundSpeed	track	time	lat	lng	dtPhase	Start	ATOT	ALDT	AOBT	AIBT	BART	THRT	taxiway	stage	duration_s	vz	cco_cdo
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	0	0:00:00	56.9227885	23.9775132	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	3	0:00:18	56.9230406	23.9775543	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:22	56.9232927	23.9775954	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:24	56.9234554	23.9775143	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:28	56.9234812	23.9769872	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:32	56.9235037	23.9763262	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:36	56.9235261	23.9760653	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:39	56.9235487	23.9756043	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:43	56.9236727	23.9752175	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:46	56.923886	23.9751345	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:51	56.9242007	23.9752192	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:54	56.9244411	23.9752708	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:02:58	56.9246889	23.9753125	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:03:01	56.9248993	23.9753457	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:03:04	56.9251504	23.9753867	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:03:08	56.925433	23.9754329	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							
EVRA	ADES	IND6	M	10	DEP147	18	TX	gate104	0	15	0:03:13	56.9257152	23.9754379	0:00:00	0:06:51	0:00:00	0:06:11	TX	4	0	0							

Figure 4 - Example of Input file for AERMOD.



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.

3 Description of the emission rates calculation

Pollutant emissions and fuel consumption are evaluated considering a combined gas turbine and combustion chamber surrogate model. This model, developed by RUBS and TUBS in WP2 and delivered as D2.2, predicts CO₂ and non-CO₂ emissions, in particular, CO, NO_x and UHC as a function of turbine design and mission conditions. Further details of the model are provided in deliverable D2.2.

This model was afterwards integrated on the Multidisciplinary Design and Optimization (MDO) framework and over the aircraft mission(s) to obtain the corresponding emitted pollutant masses and fuel consumed. Attention is given to the flight segments below 900 m, which are used here to assess airport-vicinity emissions. Within the MDO tool, the surrogate is parameterized by mission power, converted from throttle setting, an optional maximum power scaler, and operating variables such as altitude, Mach number and spool speed. Other variables include compressor pressure ratio and combustor outlet temperature. Outputs comprise compressor pressure ratio, Power Specific Fuel Consumption (PSFC), combustor outlet temperature and emissions. These are stored in a lookup database and accessed via linear interpolation, enabling fast mission level evaluation of fuel burn and emissions at fixed turbine design per iteration. Full specification of the surrogate inputs and outputs, parameter ranges and integration within the MDO process are documented in deliverable D5.2.

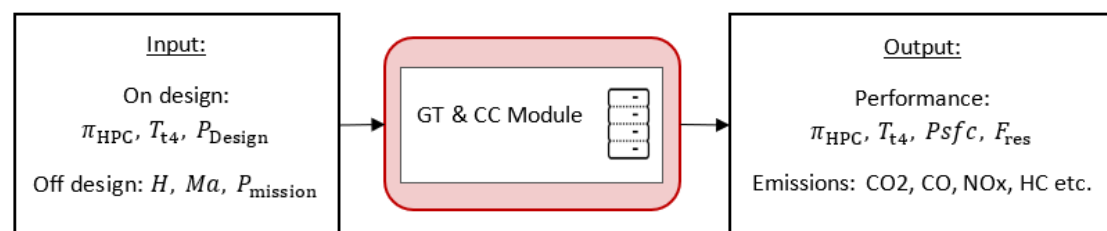


Figure 5. Block diagram with the inputs and outputs for gas turbine and combustion chamber surrogate. Reproduced from deliverable D3.2.

As previously mentioned, this module was integrated into the MDAO framework, as described in Deliverable D5.2. For the different trajectories considered in the present deliverable, the optimization objective was the minimization of block fuel, defined as the total fuel consumed by the aircraft over the nominal mission.

For all cases, the powertrain architecture and sizing were kept fixed, together with the aircraft airframe configuration (IND2), whose main geometrical parameters are



reported in Table 2. Consequently, the optimization did not involve aircraft or powertrain level sizing variables. Instead, the optimization variables were restricted to quantities that can be actively controlled during the mission, including propulsion system throttle settings, the local hybridization factor, and ψ , defined as the fraction of the total thrust generated by the outboard branch of the hybrid-electric propulsion system.

Table 2 - Aircraft IND2 airframe parameters.

Component	Parameter	Description	Value
Wing	AR [–]	Aspect ratio	21.62
	λ [–]	Taper ratio	0.42
	t/croot [%]	Root thickness-to-chord ratio	18.0
	t/ctip [%]	Tip thickness-to-chord ratio	9.0
	Sw [m ²]	Wing planform area	122.4
Strut	cstrut [m]	Strut chord	1.6



4 Description of the low-fidelity model and simulations

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 (AERMIC) 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 (EPA, 2026).

There are two input data processors that are regulatory components of the AERMOD (AERMOD, 2026) modelling system:

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

4.1 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.

4.2 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...).





Figure 6 - Example of trajectories generated by RAMS at Riga's airport.

This information is converted into the following AERMOD input files, by dividing the trajectory into different segments:



Figure 7 - Example of trajectories converted into segments at Riga's airport.

- The **HRE file** specifies the emissions for every segment of each selected trajectory for every hour of a specific period.



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- 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 receivers (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 receiver 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
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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
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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 8 - Example of a PLT output file.



4.3 Pollutant dispersion (PD)

The model has been adapted to capture the pollutant dispersion every 5 minutes, by changing the times (from the default value of 1 hour to 5 minutes) and by adapting the code and post-processing to capture the position of the clouds of pollutants at every instant.

A set of tracks (31 for conventional aircraft and 13 for INDIGO) has been independently simulated. Each segment of the track has been represented as a 3D line. The model takes into consideration the wind direction and velocity to estimate the position and transport of the primary emitted pollutants in a defined receptor grid (8x16km to the East of Riga's airport and Y axis centered on the ARP).

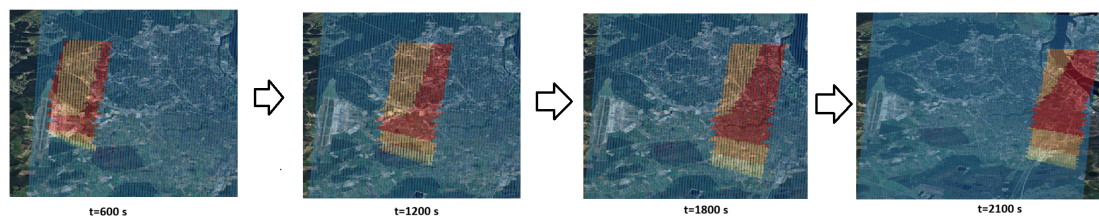


Figure 9 - Example of dispersion of CO over Riga at different simulation times measured at 1.5-meter height.

Pollutant concentrations are measured at 1.5, 3 and 4 meter height, belonging to the breathing zone, as stated in the Regulations identified in D1.1 (INDIGO Project, 2023).



5 Description of the high-fidelity model and simulations

In this section the methodology followed in the high-fidelity simulations is explained. The purpose of such methodology is to establish a procedure to produce accurate simulations in the frame of Large Eddy Simulations (LES), keeping the computational cost limited considering that a set of tens of trajectories had to be addressed. First, the underlaying assumptions will be stated, then the different steps of the methodology will be detailed and, finally, in next section, results will be presented including the comparison with low-fidelity simulations.

Calculations were performed for air traffic in Riga airport but the methodology presented is general as long as the hypothesis are fulfilled. Different to low-fidelity simulations, these high-fidelity ones are not intended to reproduce the airport operation during long times since this would incur a prohibitive computational cost. On the contrary, flights are isolated to study the behaviour of pollutants transport. Even there could be manners of accounting for the additive effect of the different flights, this has not been explored in the current project.

5.1 Hypotheses

As in any modelling in physics there are some phenomena that have to be put aside or at least simplified to bound the computational cost while having feasible simulations. To not compromise the fidelity of the results such not retained phenomena cannot be of first order. In the following the assumptions made in this work are stated:

- Only one single trajectory is computed per simulation. Therefore, each of the trajectories composing the set of simulations is carried out in a separated simulation. Such decision was taken based on the facts that reproducing the airport operation during a long enough representative time involved huge resources while separating the flights allowed to run several cases at the same time (as different simulations). Moreover, reproducing the airport operation would have complicated the data fusion step.
- Taxi phases are not considered: after a previous analysis of the trajectories it was observed that the emissions issued during the taxi-in and taxi-out phases are limited compared to the rest of phases.



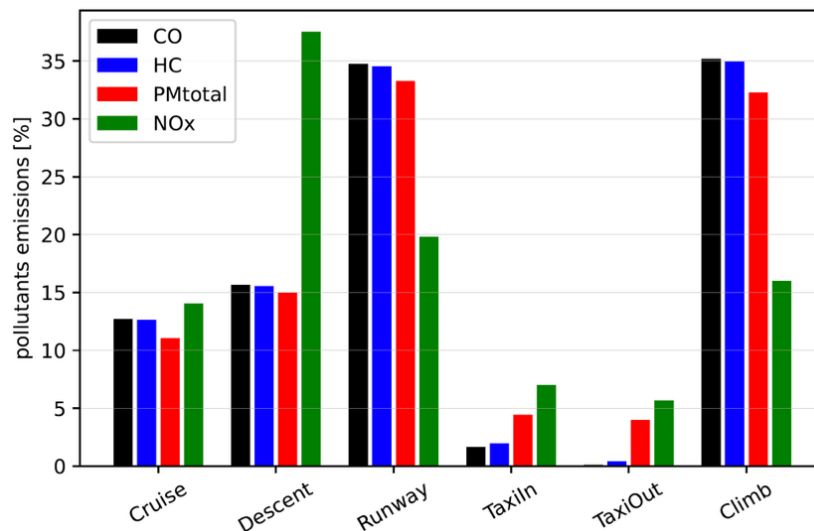


Figure 10 - Pollutant share between phases for the conventional aircraft trajectories.

- This approximation significantly reduces the duration of the flight trajectory, which after it lasts approximately for 1 minute and 30 seconds (below 900 m). Given the moderate wind conditions (in the order of 1 m/s at a height of 10 m), the effects of convection and diffusion on the pollutant cloud are negligible during the time required for the aircraft to complete the trajectory. Furthermore, because the pollutant dispersion simulations extend over at least one hour of physical time, any convection and diffusion occurring during this initial 1 minute and 30 second period has no significant influence on the results after the initial stages of the simulation.

These appreciations allow to simplify how the cloud of pollutants is introduced in the calculations: instead of considering moving sources during the flight trajectory, which mimic how the pollutants are introduced in the domain during the flight trajectory as the aircraft advances, they are instead imposed as an initial condition. Moreover, such simplification has multiple advantages:

- Greater numerical stability than introducing sources in the transport equations.
 - As will be seen in the following it allows to perform simulations at two levels of detail or at two scales. This in turn permits greater accuracy since more suitable meshes can be used at each scale.
- Due to the large extension of the original domain ($16 \times 8 \times 0.9 \text{ km}^3$), the domain was divided into two subdomains, north and south, including each one the north and the south runways of the airport, respectively. In such a way the domain had dimensions $8 \times 8 \times 0.9 \text{ km}^3$. For some of the cases where the wind was almost parallel to the trajectory projection domains of size $5 \times 12 \times 0.9 \text{ km}^3$ were used instead (with the longest side



parallel to the trajectory) to be able to capture the pollutants evolution for a longer temporal window.

- 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 even if during the long simulated periods there could be variations of such magnitudes according to the registers. Considering such variability would have introduced a difficulty in the data fusion process and its later application to the low-fidelity simulations corrections while it would not have introduced a clear benefit.
- Terrain was assumed flat and no buildings were considered. For the Riga airport terrain undulations are scarce and isolated with limited height of 30 m (terminal, control tower and some airport dependencies are the main buildings). For the sake of simplification they were omitted.
- Simulations were carried out assuming constant flow properties (density and viscosity) and no atmosphere thermal stratification was considered.

5.2 Governing equations and numerical set-up

The transport equations to be solved correspond to continuity, Navier-Stokes and pollutants. 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. Assuming Boussinesq and gradient diffusion hypotheses to model the turbulent transport in Navier-Stokes and pollutants transport equations, the equations solved are:

- Continuity

$$\nabla \cdot \bar{u} = 0$$

- Navier-Stokes

$$\frac{\partial \bar{u}}{\partial t} + \nabla \cdot (\bar{u} \otimes \bar{u}) = -\frac{1}{\rho_0} \nabla \bar{p} + \nabla \cdot (2(\nu + \nu_t) \bar{S})$$

- Pollutants

$$\frac{\partial \bar{Y}_i}{\partial t} + \nabla \cdot (\bar{u} \bar{Y}_i) = \nabla \cdot \left(\left(\frac{\nu}{Sc} + \frac{\nu_t}{Sc_t} \right) \bar{Y}_i \right)$$

where u is the velocity, S the strain rate tensor, p the modified pressure, which accounts in addition for the sub-grid turbulent kinetic energy (Boussinesq hypothesis), and Y_i corresponds to the mass fraction for the i -th species. Moreover, ρ_0 is the ambient density (constant) and ν and ν_t are the molecular and turbulent kinematic viscosities, respectively. The Sc and Sc_t are the laminar and



turbulent Schmidt numbers, respectively. Bars over the variable denote filtered quantities.

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) (Vázquez et al., 2016). 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 (Castillo and Codina, 2014; Houzeaux and Príncipe, 2008). 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. The mesh of $5 \times 12 \times 0.9 \text{ km}^3$ is defined in a similar manner. Mesh nodes and cells are also 100.9 M and 99.97 M, respectively.

To completely define the problem proper initial and boundary conditions have to be provided. In the following attention will be devoted on their definition based on the scale separation method developed in the project.

5.3 Initial conditions

Initial conditions for both velocity and pollutants mass fractions are needed. To this end the domain is divided into two parts, a first one affected by the flight of the aircraft in terms of velocity and pollutants, and a second which is assumed to not have been perturbed by the aircraft flight. This is done by virtue of the time that the flight lasts, which as mentioned lines above is limited to the order of 1min 30s approx.

To create the initial conditions for the region affected by the flight an envelope is defined around the flight trajectory whose surface separates this region from the unperturbed one. The effect of the aircraft on the air is created by simulating the



reaction of lift and drag on the air and the interaction of the induced air motion with exhaust gases plumes. Since the mesh of the nearby airport has not enough resolution, precursor simulations are carried out to predict the interaction of the aircraft with the air.

To this end, simulations in a tri-periodic cuboid domain are carried out (intermediate scale simulation). The reaction of lift and drag are imposed on a thin sheet along the flight direction movement following elliptical profiles according to Lin et al., 2017. For conventional aircraft elliptical profiles for lift and drag are used while for the solution one profiles are computed from RANS (Reynolds Averaged Navier-Stokes) of the aircraft since real profiles deviate remarkably from ideal ones. Such volumetric forces are imposed for a short period of time after which they are removed to let the air evolve in the absence of any external action. Moreover, the exhaust gases plumes are positioned considering the geometry of the airplane by defining unity value for a general scalar (zero outside) that represents any pollutant. Isotropic homogeneous turbulence is imposed in the velocity initial fields to reproduce the chaotic movement of air in the atmosphere prior to the aircraft interaction (absence of winds). During the air motion the main effect caused by lift comes from the wing-tip vortices created by the strong gradients of this force at the tip of the wing which engulf the plumes creating highly turbulent vortices.

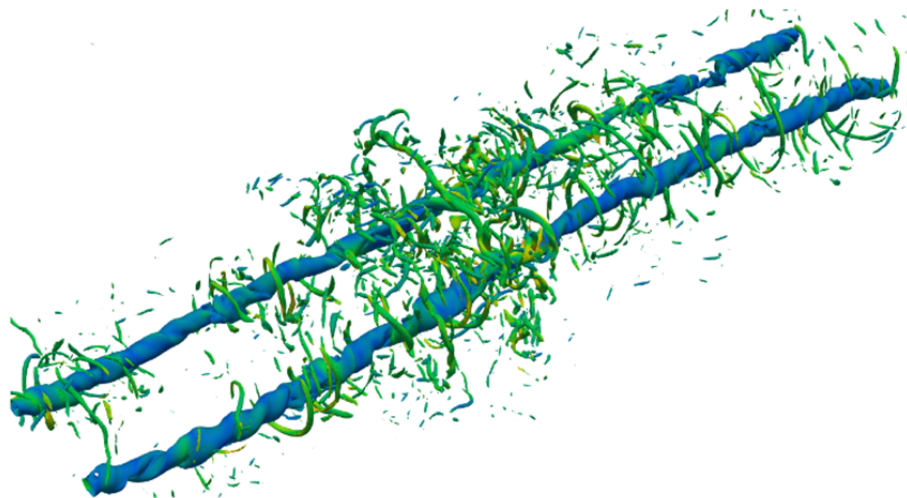


Figure 11 - 3D view of the wing-tip vortices.



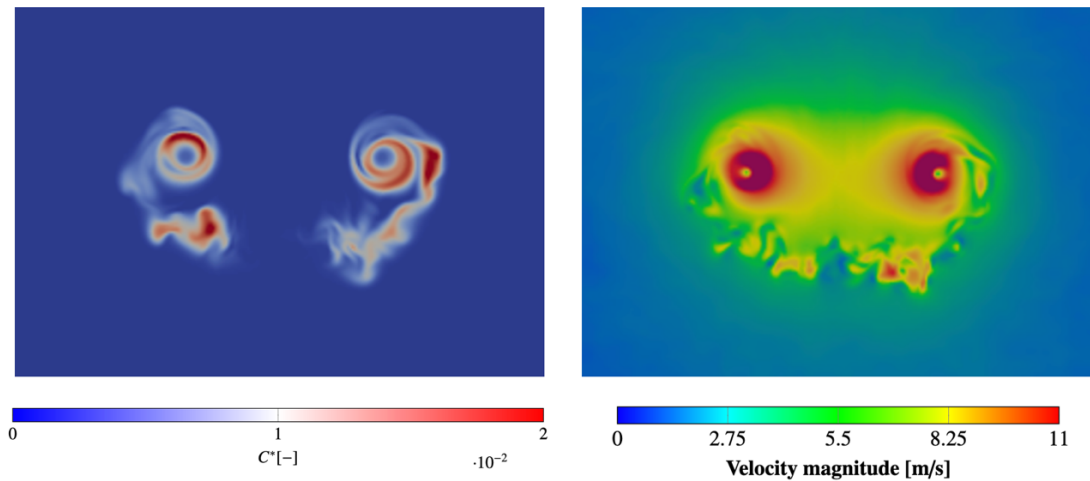


Figure 12 - Slice of the wing-tip vortices created by the interaction of the aircraft with the air. The plane is normal to the aircraft trajectory. Left: scalar field representing the pollutants; right: velocity magnitude field.

In order to use the fields from these simulations for the initial conditions of the nearby airport one (large scale simulation), results from previous simulations are stored in a database. Such database saves the velocity and the generic scalar field and is parametrized as a function of the circulation, directly related to the aircraft velocity, and time. In the large scale simulation, time from the database corresponds to the age of the vortices, that is, the time elapsed since they are incepted (instant at which the aircraft passes through a point of the trajectory) till the time the aircraft finishes the trajectory.

The database gathers data for circulation (aircraft velocity) at least as high as that found in the trajectories and a time that exceeds the temporally longest trajectory. Two databases are created, one for the conventional aircraft and other for the solution airplane.

Trajectories are provided as a set of discrete points at which spatial coordinates, velocity and pollutants mass fractions are given. Such points define segments where previous magnitudes are assumed to evolve linearly (piecewise linear interpolation). Based on these considerations velocities and pollutants mass fractions are assigned to each of the points of the envelope (perturbed region) after linearly interpolating values in the manifold.

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. The calculation of the corresponding turbulent boundary layer for each of the cases would lead to an unacceptable computational cost. Therefore, to drastically reduce the computational cost of such computations, a precursor simulation is carried out for a representative turbulent boundary layer. Such boundary layer is defined with a wind velocity that approximately corresponds to the mean of the wind velocities of the



trajectories. The wind angle is chosen such that is parallel to two of the lateral faces. The precursor simulation is run for a time long enough to assure that the flow is statistically stationary. For the final simulations the velocity field from the precursor simulation is mapped to the nearby airport simulations after being scaled, to achieve the corresponding mean wind velocity modulus, and rotated, to align with the wind direction.

In this precursor simulation the inlet boundary condition corresponds to the mean velocity profile for no thermal stratification. Therefore, not the whole precursor simulation is usable for mapping since there exists a transition from the laminar inlet condition (no fluctuations at the inlet boundary) to a fully developed turbulent flow. Moreover, the turbulent boundary layer thickness is consistently increasing in the absence of obstacles. Then a relatively small region, in the current simulations a parallelepiped of sizes $2 \times 2 \times 0.9 \text{ km}^3$, is mapped repeatedly into the final domain. The position of this volume is taken such that the boundary layer has reached a representative height of around 200 m. Such volume is big enough to consider that points at opposite faces are uncorrelated. Therefore, the impact of repeating the same structure several times should not have effect.

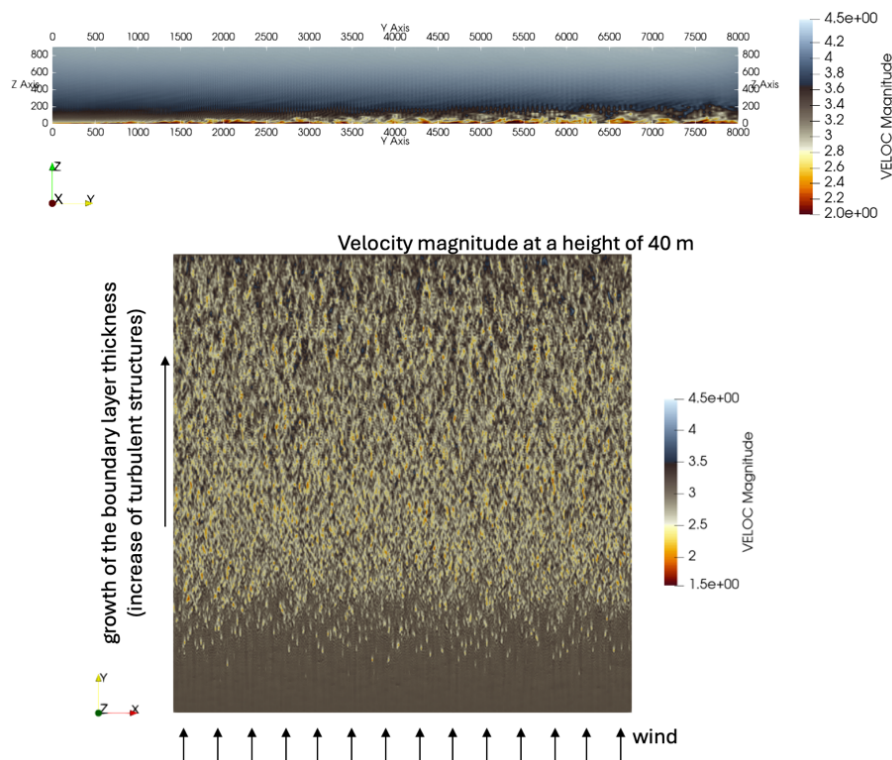


Figure 13 - Velocity magnitude field (in m/s) for the turbulent boundary layer from the precursor simulation. Top: slice parallel to the mean wind direction and perpendicular to the ground. Bottom: slice parallel to the ground at 40 m height.



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.

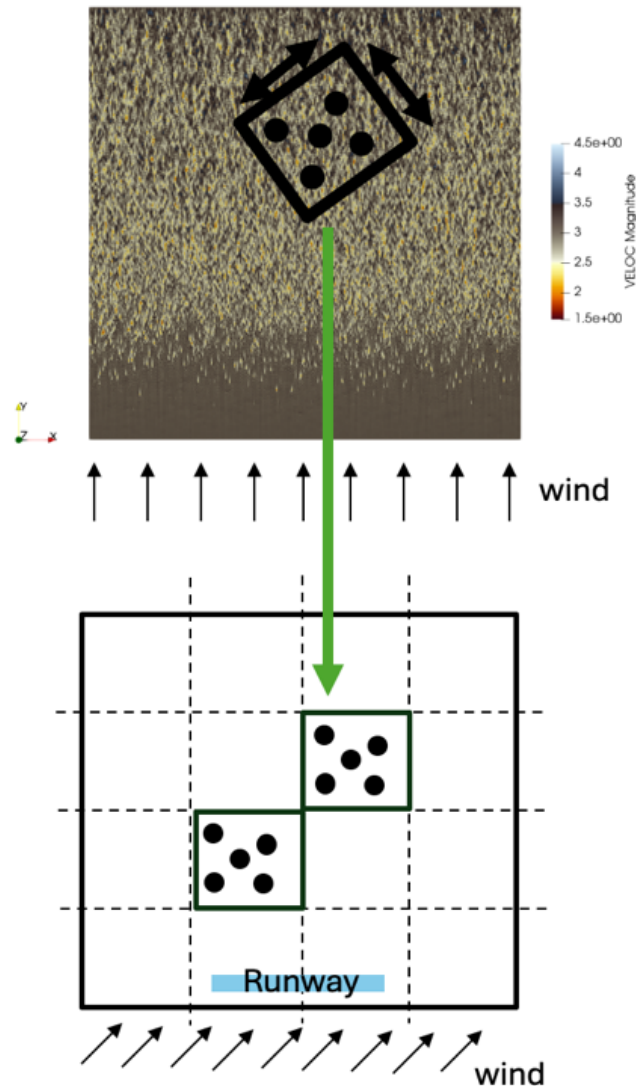


Figure 14 - Sketch of the procedure to map the velocity field from the precursor simulation to the nearby airport region in the zone unperturbed by the aircraft.

5.4 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.
- For top a slip condition could have been chosen. In this case, however, 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:



$$v(z) = \frac{v_\tau}{\kappa} \ln \frac{z}{z_0},$$

being the friction velocity v_τ computed from the knowledge of the velocity at 10 m height V_{10} , data which was taken from experimental measurements at the airport:

$$v_\tau = \frac{V_{10} \kappa}{\ln \frac{10}{z_0}}.$$

In previous equations, κ is the von Karman constant which values 0.4 and z_0 is 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 (clearly this depends on the wind direction) from the domain an outlet condition was imposed (null gradient). This is may not be a completely accurate boundary condition for the turbulent boundary layer but it was used, on the one hand, because of its simplicity and, on the other hand, since it was checked that its effect upstream the faces was very limited. Therefore, only in a small fringe very close to the affected faces solutions were not fully trustable as a consequence of this boundary condition.
- For the lateral walls of the parallelepiped through which the wind enters (clearly this depends on the wind direction) into 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 sections following similar ideas to those applied to inlet conditions in pipes for high Reynolds internal flow.

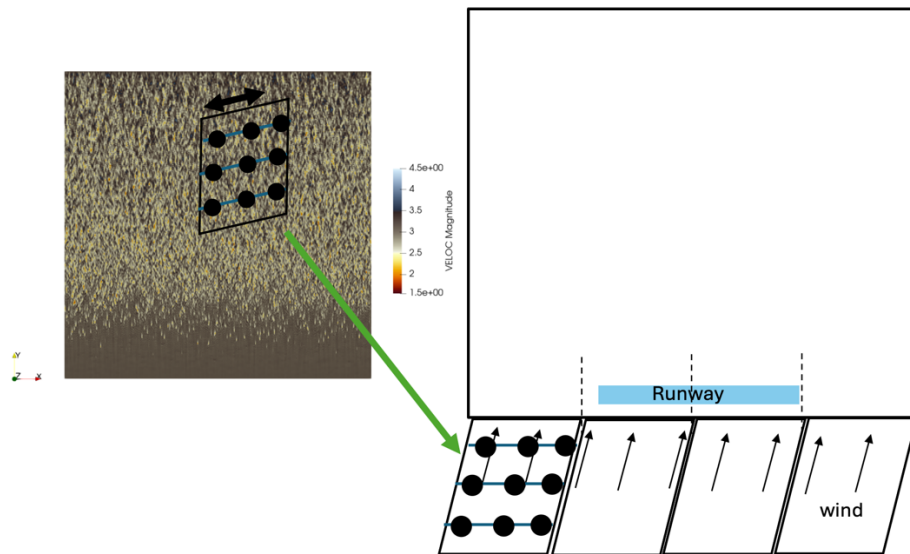


Figure 15 - Skecth of the procedure for the generation of the turbulent inlet boundary conditions.

As seen from the figure different vertical planes or layers (in the figure the layers become a line, the intersection between the vertical plane and the horizontal plane of the representation) are saved in a database as a function of time (the number of layers in the figure is merely illustrative). The relationship between such time and the separation of the layers is defined by the average velocity of advancement of the fluid. Between points of different layers linear interpolations are performed. The angle of the layers is defined based on the direction of the wind in the large scale simulation. Finally, to say that the database is read cyclically. Because the domain is too big compared to the precursor simulation the layers are replicated.

In the following some illustrations for the initial and boundary conditions are shown.

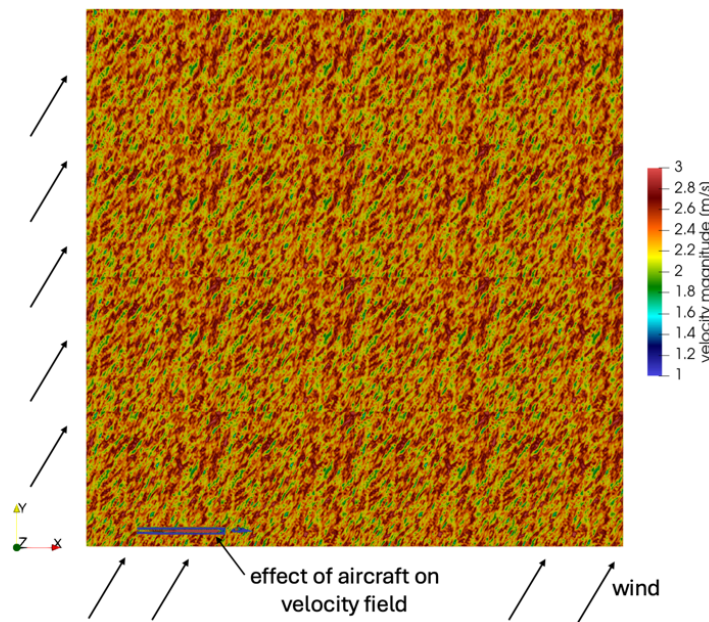


Figure 16 - Velocity magnitude initial field for a horizontal slice at 40 m height. The perturbation of the aircraft in the field is observed close to the bottom side. Scale is saturated to improve the visualization of the structures of the flow.

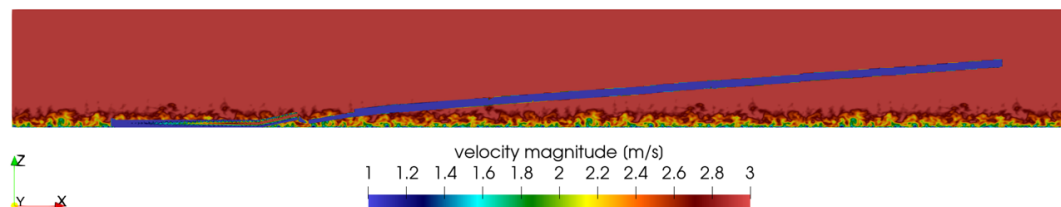


Figure 17 - Velocity magnitude initial field for a vertical slice parallel to the trajectory. The plane cuts part of the vortices created by the aircraft. Scale is saturated to improve the visualization of the structures of the flow.



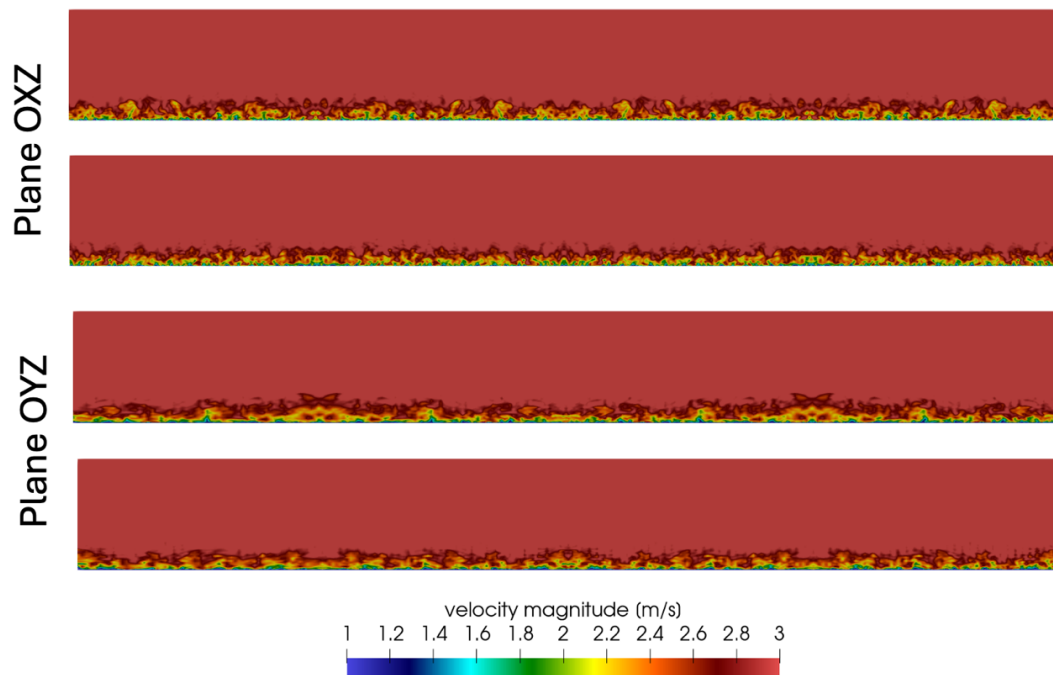


Figure 18 - Snapshots for the velocity magnitude for inlet boundary conditions. Scale is saturated to improve the visualization of the structures of the flow.

Representations of the CFD solutions are given in the following to illustrate the fields obtained in the simulations.

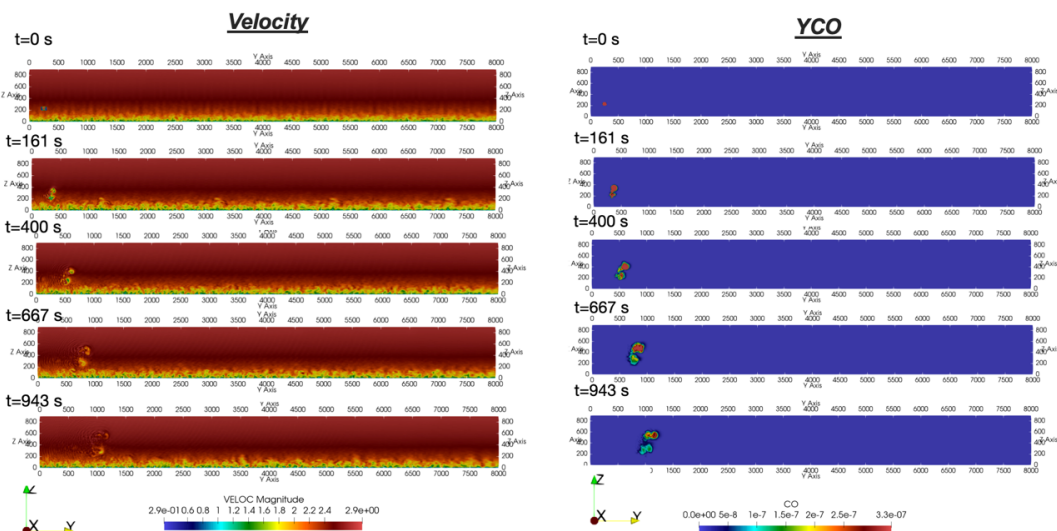


Figure 19 - Representation of velocity magnitude in m/s (left) and the CO mass fraction (right) in vertical slices normal to the trajectory over time.

Finally, 3D views are shown to illustrate how the cloud of pollutants is dispersed, convected and mixed with the surrounding air during the first 30 minutes.



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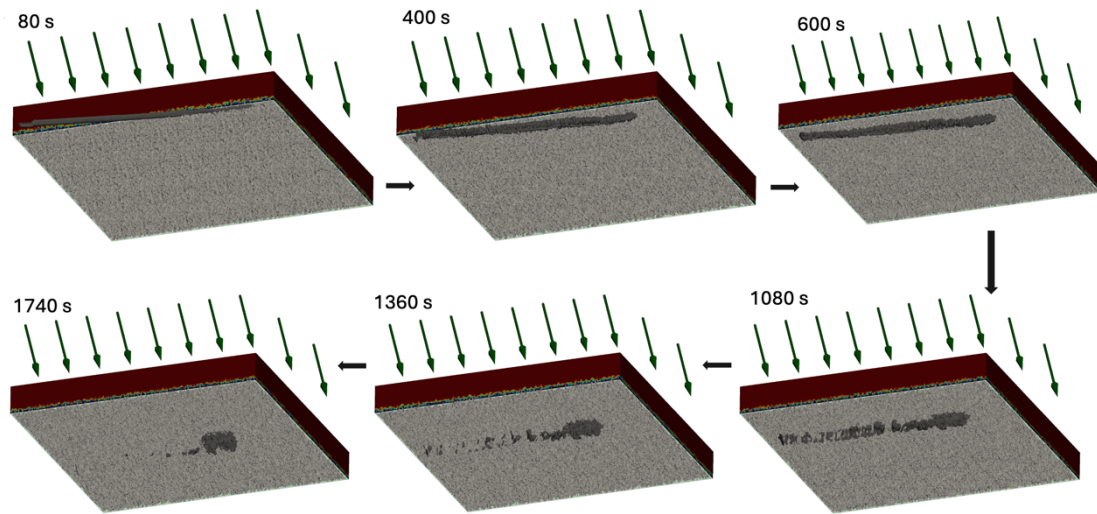


Figure 20 - 3D views of the dispersion, convection and mixing of the pollutant plumes left by the aircraft. For visualization purposes only the inlet lateral faces are shown. An isosurface of the velocity magnitude is included to illustrate the flow structures (grey layer at the bottom). Green arrow in each of the figures indicate the direction of wind. Black arrows indicate the direction in which time advances.



6 Comparison of the high- and low-fidelity simulations

Simulations for conventional and the solution aircrafts were performed with a total of 31 cases for the conventional aircraft and 13 flights for the solution one. Solutions were postprocessed each 5 minutes of physical time and comparison between high- and low-fidelity was carried out in a set of probes at 1.5, 3 and 4 m height uniformly distributed over the domain with a minimum separation of 100 m.

For the high-fidelity direction, as explained previously, the mesh is identical for both north and south subdomains with the x direction parallel to the trajectory projection. Because of the orientation of the Riga airport the x direction is not parallel to the south-north direction but is slightly rotated in the clockwise direction. Therefore, the solutions obtained in the mesh for the high-fidelity simulations were accordingly rotated and translated to extract the information on the corresponding probes.

As said, the pollutants transported in the (low- and high-) simulations are carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons (UHC) and particulate matter (PM). An illustrative comparison between both models is shown in the following for a landing and a take-off of the solution aircraft.

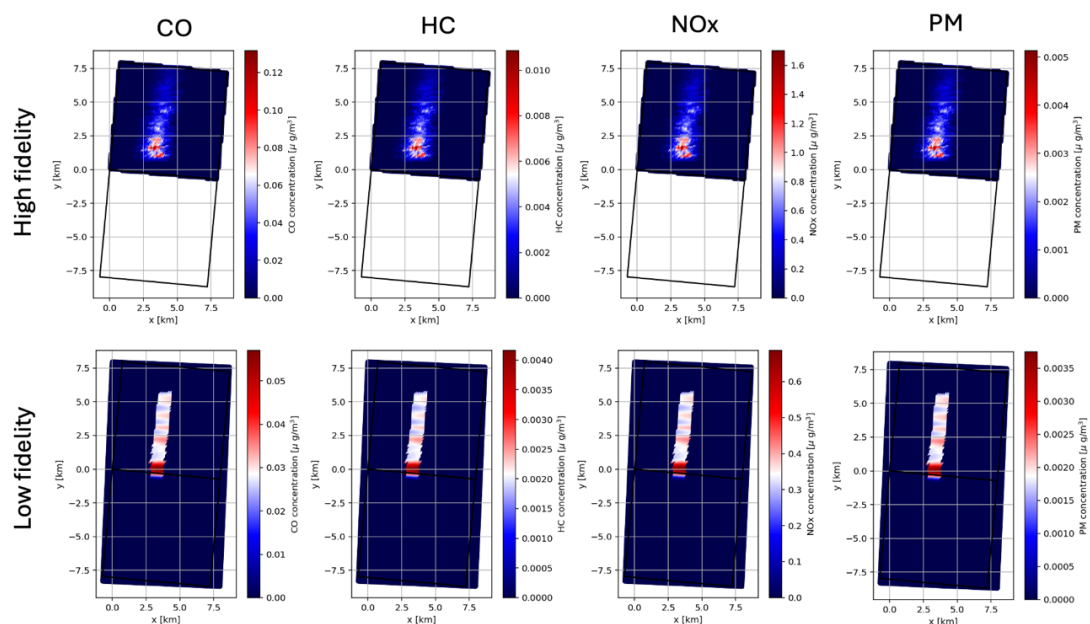


Figure 21 - Comparison of high (top row) and low fidelity (bottom row) simulations for different pollutants at a height of 1.5 m. Solutions for the landing of the solution aircraft after 2400 s after the end of the trajectory. Wind velocity of 1.54 m/s (10 m height) and wind direction of 270°.



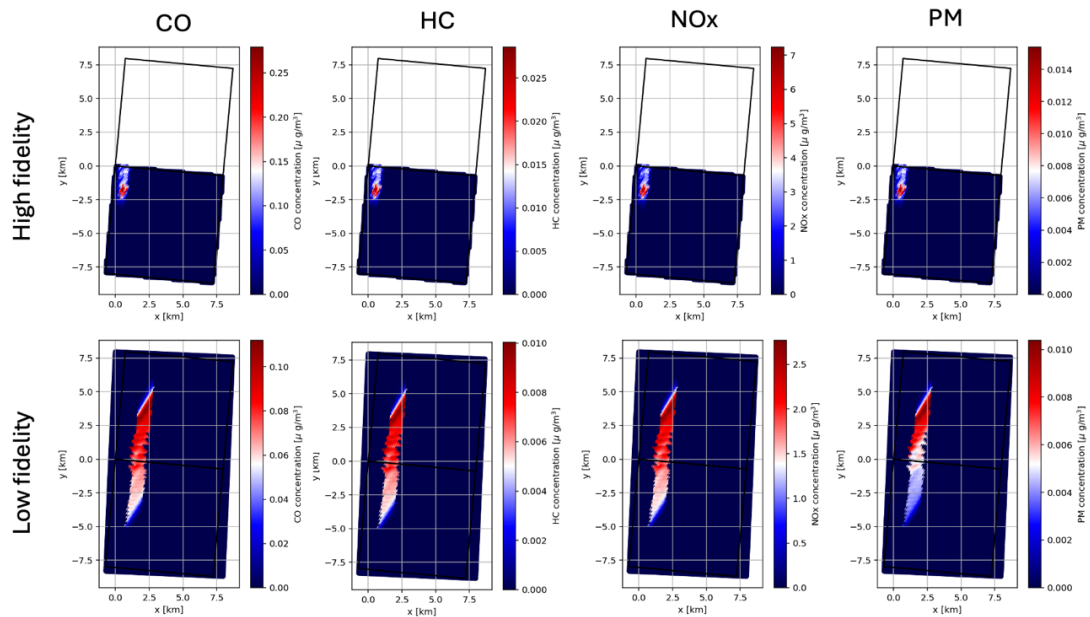


Figure 22 - Comparison of high (top row) and low fidelity (bottom row) simulations for different pollutants at a height of 1.5 m. Solutions for the take-off of the solution aircraft after 1500 s after the end of the trajectory. Wind velocity of 1.54 m/s (10 m height) and wind direction of 210°.

In general, the low- and high-fidelity simulations show a qualitative resemblance regarding the pollutants cloud shape even important differences are observed. As expected the high-fidelity simulations provide maps with high fluctuations levels caused by turbulence while the low-fidelity simulations, on the contrary, predict soft fields as averaged fields are computed.

Finally, to mention that, as explained previously, for the high-fidelity simulations only either the north or the south subdomain was computed (exceptionally in some cases the domain extended partially over the two subdomains) and, one of them remains with no data as can be observed in the figures.

The data fusion, explained in next section, is intended to remedy the inaccuracies of the low-fidelity simulation by correcting them based on the fields provided by the high-fidelity ones.



7 Algorithms for data fusion

Data fusion is realised between the available high-fidelity and low-fidelity data with the goal of generating a corrective model for future AERMOD computations. The outputs of this methodology are two-fold. Primarily this approach is intended to improve the estimates of local air quality metrics obtained by assessing the cumulative polluting effect of the many trajectories associated with typical daily to annual airport operations. Since high-fidelity LES simulations are prohibitively expensive in this context, the already available data must be leveraged in a data-driven manner. A secondary use case of the data fusion model arises from the fact that the correction factors could be considered general and airport-agnostic and thus applied to air traffic elsewhere in the world, not only pertaining to RIX. It must be noted here however that this secondary use case is out of the scope of the outcomes presented in this deliverable. It is theoretically allowable by the methodology presented here but would likely need a more carefully considered parameterisation and dataset.

The datasets are treated with a reduced order method. Constructing a data-driven Reduced Order Model (ROM) allows for the implicit representation of underlying physics connecting trends in pollutant dispersion and characteristics of flight trajectories. The algorithm used here is non-intrusive snapshot-based Proper Orthogonal Decomposition (POD). This enables a fully parametric description of each constitutive snapshot and dispenses with any need for knowledge of the physical system (e.g. governing equations). High-dimensional solution approximation is performed instead using Radial Basis Function (RBF) interpolation driven by specifying a full set of parameters.

This section focuses on the high-level outline of the methodology or *data fusion workflow*, detailing each step in the workflow thereafter. A special consideration is given to assessing the error of the corrective model, hereafter referred to as confidence level. The main steps of the workflow are as follows:

1. Parameter space definition
2. Data pre-processing
3. Generation of ROM
4. Estimation of model error
5. Use of model ‘online’ to correct “new” AERMOD simulations
 - a. Obtain corrected LAQ KPI
 - b. Predict improvement of solution (INDIGO) over reference (conventional) aircraft



7.1 Parameter Space Definition

The parameter space must be chosen with care so that it represents well the main factors driving the system dynamics, in this case the dispersion of emitted pollutants. On the basis of available metadata associated with each simulated trajectory, the prevailing wind conditions are identified as primary drivers for the observed pattern of pollutant dispersion. However, with the sampling (i.e. ensemble of low- and high-fidelity simulations from T6.4) finalised *a priori*, considering solely wind conditions (direction and modulus) proves to be insufficient as it does not provide a unique parametrisation of each individual sample point. This is paramount so that nuances between similar trajectories are retained in the ROM. Therefore, *average engine mass flow rate* is introduced as an additional parameter, with the assumption that the mass flow rate directly influences the amount of pollutants emitted. Both for the INDIGO and conventional aircraft this three-dimensional parameter space is thus employed. An important note must be made here with regards to distinction between landing and take-off phases. The pollutant concentrations can be expected to differ substantially between the two phases, owing to differences in thrust requirements, ascent/descent profiles, etc. A binary parameter such as this however does not suit the parameterisation expected by the data-driven method. In the case of the INDIGO aircraft a clear, implicit distinction is made between the phases by the average mass flow rate parameter. In the case of the conventional aircraft this distinction is not clear; instead two ROMs are generated, separating the samples explicitly.



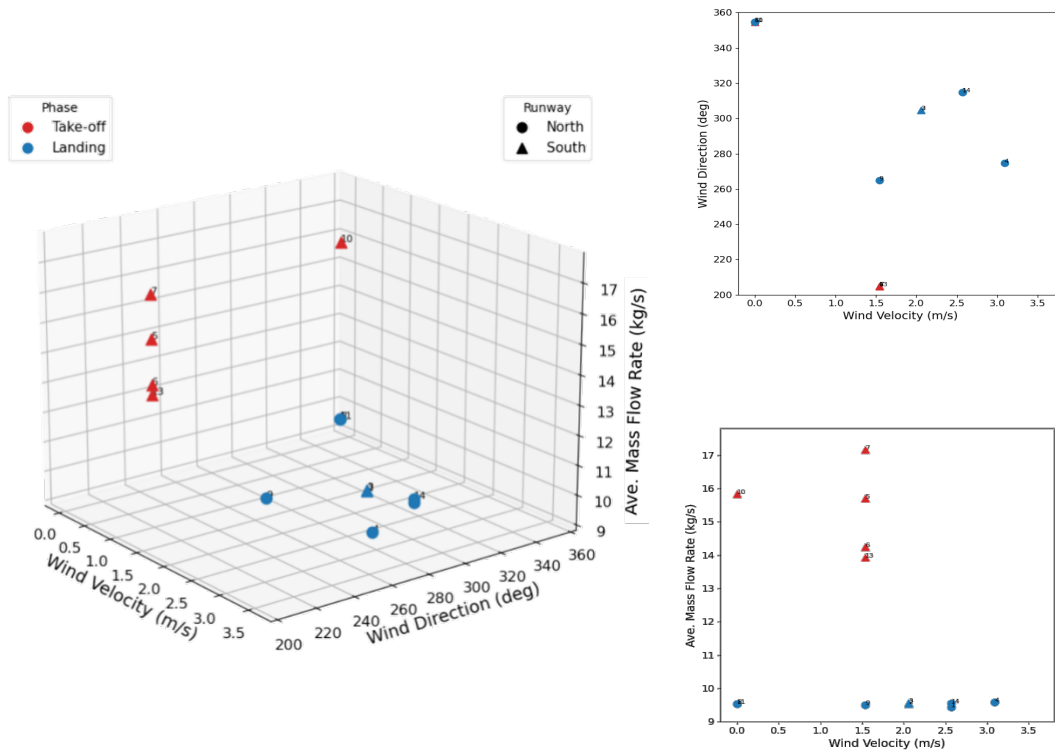


Figure 23 - Parameter space and snapshot distribution for INDIGO case. Planar projections shown on right. The LTO phase and runway are indicated here but the data is considered together.



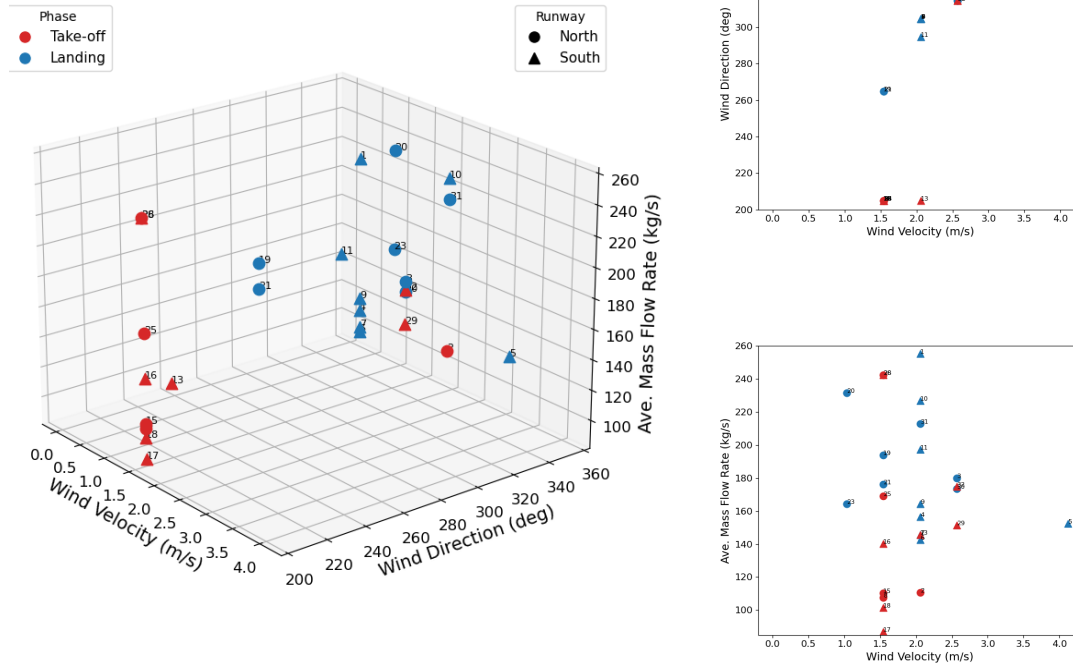


Figure 24 - Parameter space and snapshot distribution for conventional case. Planar projections shown on right. The LTO phase and runway are indicated here. Landing and take-off cases are treated separately when generating the ROM.

The parameter space and sampling are shown in Figure 23 and Figure 24. Note here that the “irregular” nature of the parameter space sampling in both cases severely limits the regions in which the ROM-based approximations can be considered to be interpolated; POD is not well suited to extrapolate as any approximation will be a weighted linear combination of the bases extracted from the constitutive data. However, within the context of the data fusion task it was not possible to extend the sampling due to the very high computational costs of the LES simulations.

7.2 Data pre-processing and generation of ROM

The snapshot ensemble is generated within this step of the workflow. The assumption for the correction is based directly on the difference of corresponding high-fidelity and low-fidelity fields and POD is performed directly on this delta in the subsequent step. Future AERMOD solutions can then be corrected simply by a summation step with the POD-based approximations of the correction field, considered separately for each pollutant species.



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Although the pollutant dispersion inherently describes a temporal evolution of concentrations, the data fusion instead considers so-called *aggregate pollutant maps*. Considering time as an additional parameter adds significant complexity for a very sparsely sampled parameter space which is likely to be to the detriment of the model itself. Moreover, the primary output of the data fusion is for the intended improvement of LAQ metric, which is defined as the cumulative effect of several, potentially overlapping flights. Using aggregate data is appropriate for this, although it requires for some post-processing of raw AERMOD results.

The data is aggregated in the following sense. The instantaneous pollutant maps are integrated over time for each measurement probe location. Since the common time interval of high-fidelity and low-fidelity data was 4500 seconds, that is chosen for the integration step. The integrated values are then averaged over each measurement height (from 1.5 to 4 metres). The difference between high- and low-fidelity data is taken after this step. An example of aggregate pollutant maps for LES, AERMOD, and their Δ is shown in next figure.

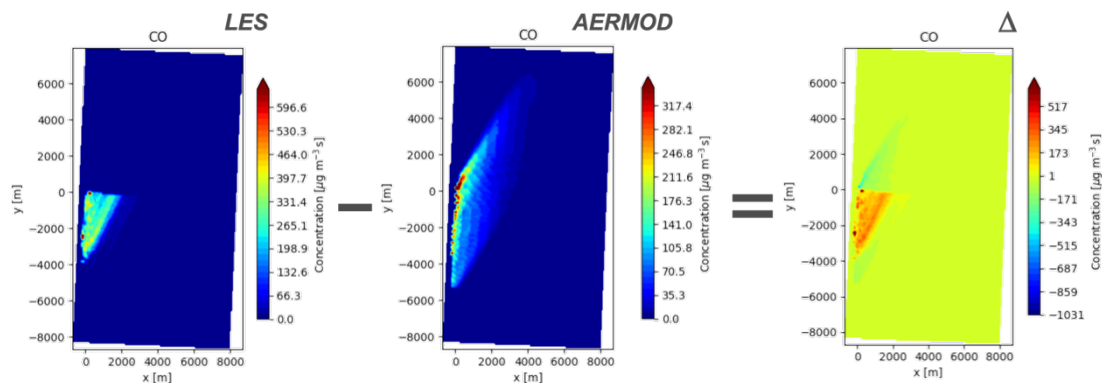


Figure 25. An example of aggregate CO concentrations for LES and AERMOD as well as their difference. The operation to obtain the latter is also illustrated.

The ensemble of snapshots is then processed using an in-house tool to generate the decomposition. The ROM and metadata are stored in a portable HDF5 database. Approximations (“reconstructions”) are computed on-demand using the same tool and on the basis of user-defined parameter combinations.

7.3 Estimation of ROM error

Establishing a confidence level in the ROM approximations is crucial for insight into the improvement that can be expected by employing the data fusion approach. To avoid generating additional high-fidelity samples that can be used purely for assessing reconstruction error directly some alternative approach is needed to estimate the error. In the context of the framework this estimate is a combination of a qualitative and a quantitative analysis.



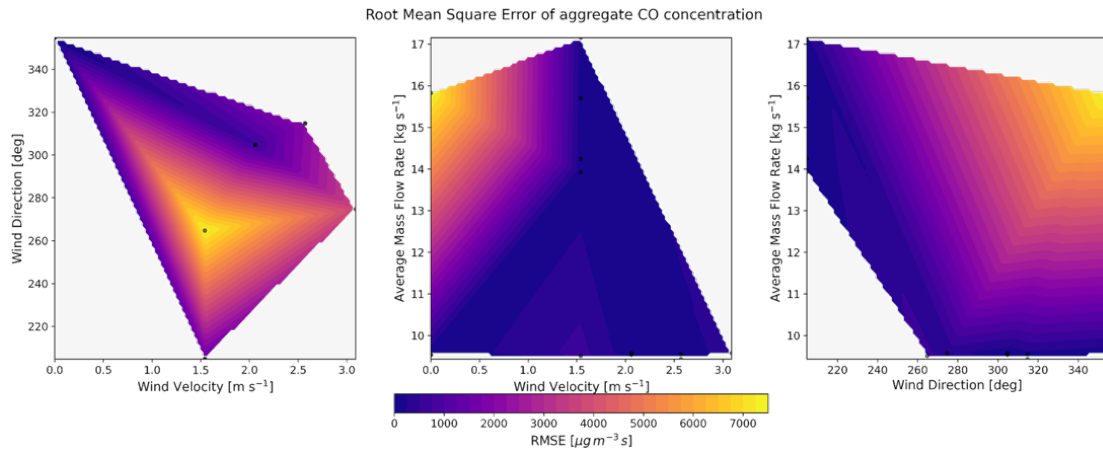


Figure 26. Leave-one-out error of CO concentrations based on ROM predictions for the INDIGO aircraft.

A leave-one-out cross-validation is performed to obtain a quantitative assessment. For each snapshot the reconstruction is determined as a single root mean square value, which is then estimated across the parameter space by way of interpolation. Due to the nature of the leave-one-out each error evaluation is performed on a depleted ROM distinct from the ROM generated from the full snapshot ensemble. Error evaluations of snapshots located at the corners of the parameter space are expected to present large inaccuracy as the reconstructions are effectively extrapolated. The leave-one-out error is shown in Figures 26-28 for the INDIGO and conventional aircraft cases respectively. Error is computed for each pollutant independently (as they are treated as independent variables, but shown here only for the case of CO).

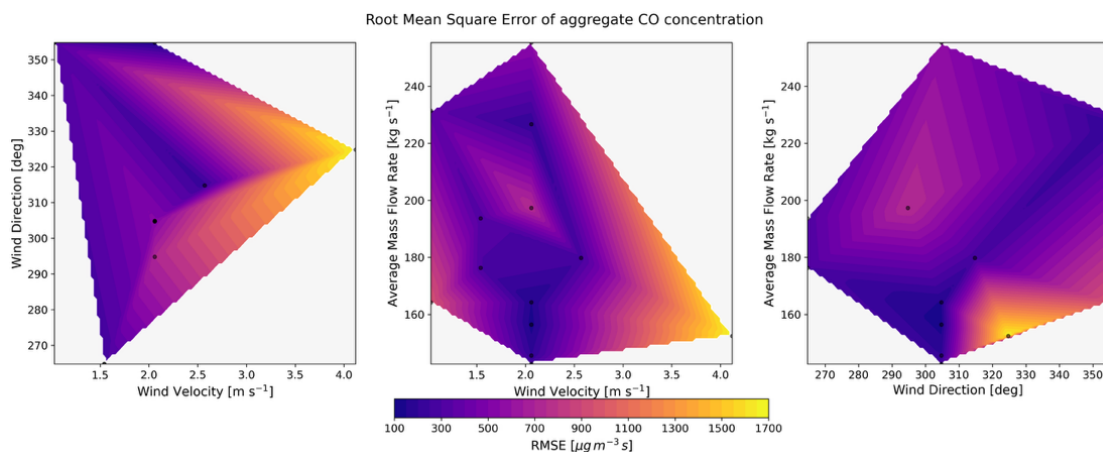


Figure 27. Leave-one-out error of CO concentrations based on ROM predictions for the conventional aircraft; landing only.



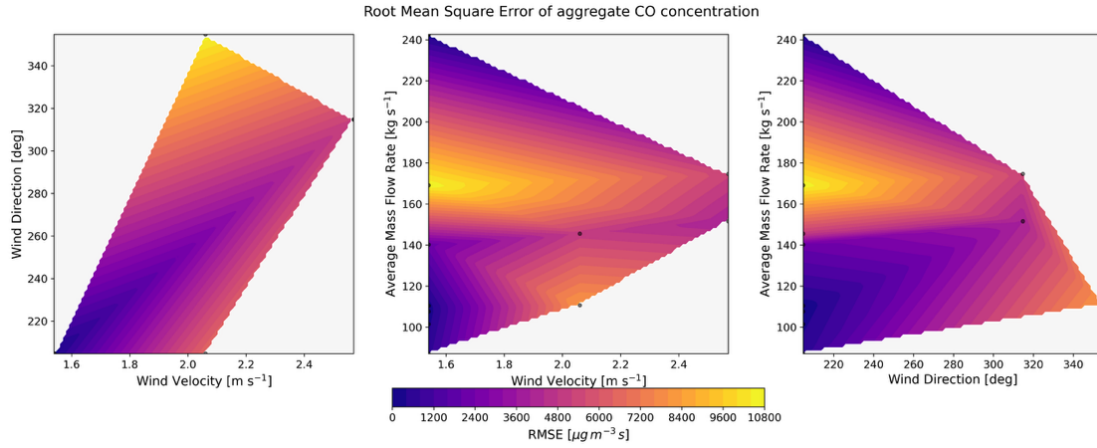


Figure 28. Leave-one-out error of CO concentrations based on ROM predictions for the conventional aircraft; take-off only.

The qualitative assessment is introduced to further inform the confidence level in reconstructions. For this analysis an assumption is made that the distribution of the *weights* (coefficients) of POD modes for a particular high-dimensional reconstruction implicitly inform how well the existing decomposition represents that point in space. For example, if the reconstruction is computed predominantly with the highest-ranked modes it indicates that the reconstructed point is near the snapshots in the low-dimensional subspace, so that the reconstruction error is expected to be relatively low. This assumption is afforded by the energy-based ordering of POD modes. The inverse can also be assumed true if the lowest-ranked modes are prevalent in the reconstruction. The error is then defined on the following basis. A reference error is expressed by reconstructing snapshots with a varying number of POD modes. Such reconstructions are exact when all modes are used. However, progressively more reconstruction error is introduced as the number of modes used is iteratively decreased. Thus, the reference error is defined for the whole range between minimum and maximum number of modes, computed from the worst snapshot reconstruction for each case. This process is repeated for each new point and the corresponding error compared to the reference. Then, if the distance from reference is small, a high confidence level is associated to the accuracy of this specific reconstruction. The error ε when using m POD modes for reconstruction is computed by $\varepsilon_m = rms[\hat{\mathbf{u}}_{N_M=m} - \hat{\mathbf{u}}_{N_M,max}]$, where $\hat{\mathbf{u}}$ is the reconstructed quantity and N_M denotes number of modes. Figure 29 shows an example with the aim to illustrate the method outlined above. Confidence level is assessed when a few modes are omitted, whose exact number is ambiguous as omitting too many modes will render most reconstructions too inaccurate and thus unsuitable for the evaluation of the confidence level. In the example case on the basis of the reference error the band between 8 to 10 modes is used



for assessment. The reconstruction of CO and PM can be assigned a medium to high level, HC a low to medium level, and NO_x a low level of confidence. Although not presented here, this assignment of confidence level would then be combined with the error estimate from the leave-one-out analysis to provide sufficient insight into the likely expected accuracy of the subsequent correction for AERMOD.

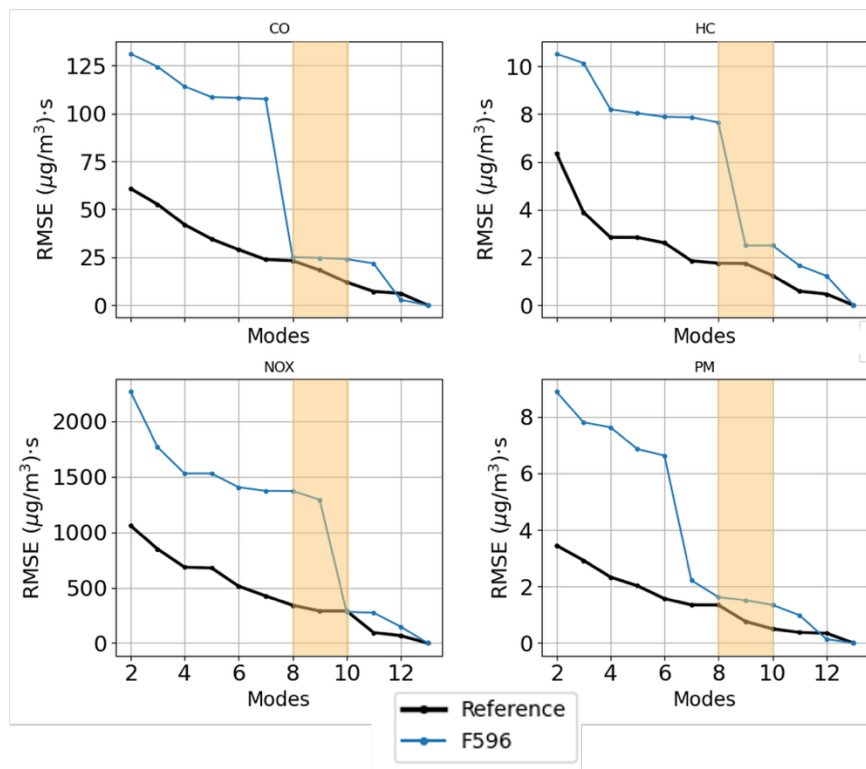


Figure 29. Demonstrative example of qualitative error analysis for ROM model of the INDIGO aircraft. The yellow bands mark the interval at which the confidence level is ascertained.

8 Application of the data fusion to the low-fidelity simulations and assessment of the improvement of pollutants predictions

The data fusion methodology updates pollutant concentrations obtained from AERMOD using the deltas calculated with the in-house ROM tool RAZOR (Nagy et al., 2022; Jones et al., 2023). As explained in previous sections the pollutants considered are CO, UHC, NOX, and PM.

The reference delta grid has a smaller coverage than the RIX receptor grid defined for the week Use Case (UC). In order to cover the rest of the domain, extrapolation and transfer procedures are required to extend the delta values from the reference grid to the target grids.

As RIX and the reference grid are associated with the same airport, although their receptors differ, the method applied for RIX differs from that used for the other airports.

For RIX (EVRA), the available deltas are first assigned to the closest receptors in the target grid. Only receptors within the defined matching distance are directly assigned a value. The remaining receptors are filled progressively using the deltas of nearby receptors. The method considers up to eight neighbouring receptors located within 150 m distance. The estimated value is calculated as a distance-weighted average: nearby receptors have a much greater influence than distant receptors. The influence decreases with the cube of the distance.

This interpolation is repeated until all receptors have been assigned a value or no additional receptors can be estimated from neighbours within the maximum distance.

To avoid extending the influence of the reference values unrealistically far from the original matched receptors, an additional distance-decay function is applied. No reduction is applied within 250 m of an original receptor. Beyond this distance, the extrapolated concentration change decreases exponentially. Consequently, concentration changes gradually approach zero in areas that are far from the available reference information.



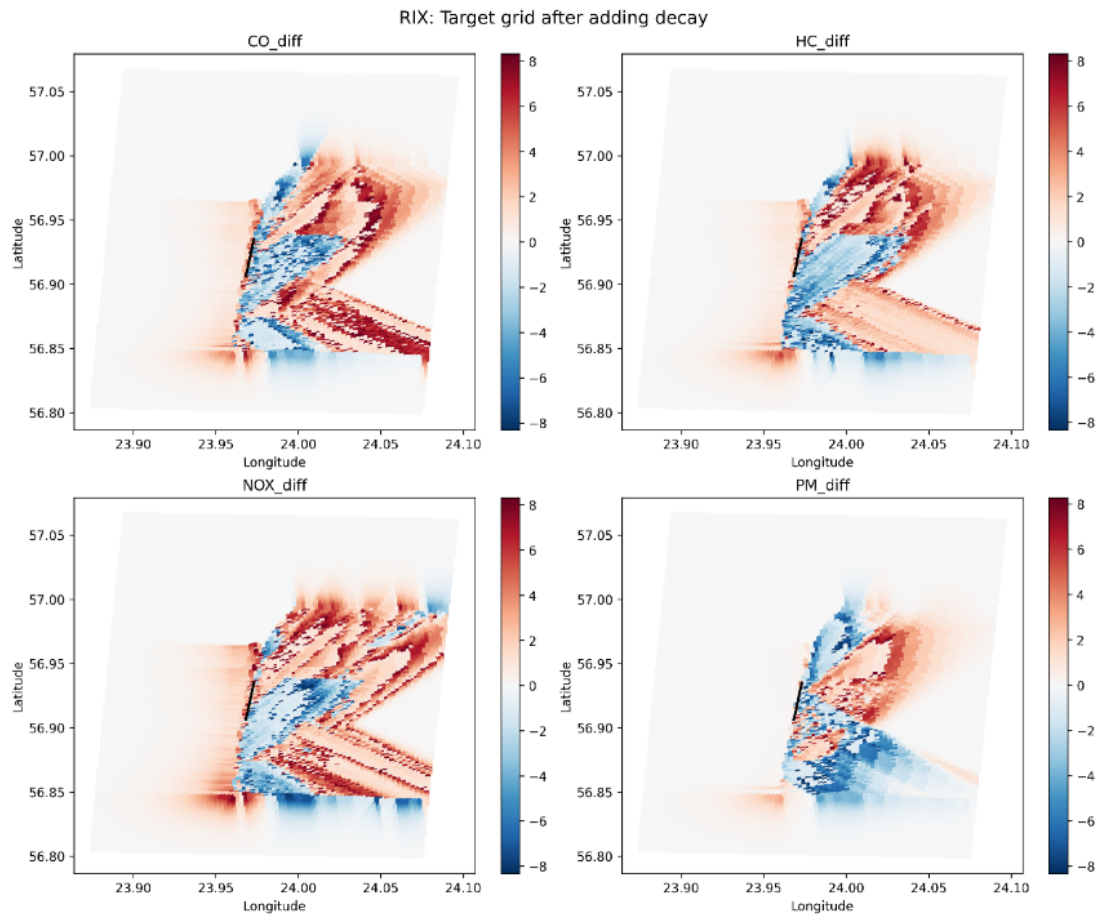


Figure 30. Deltas calculated at RIX for each pollutant and receptor.

For airports other than RIX (i.e.: Madrid, Barcelona and Dortmund), the concentration-change pattern is transferred using runway-relative coordinates rather than absolute geographic coordinates. This allows the spatial pattern around the RIX runway to be adapted to runways with different geographic positions, orientations, and lengths.



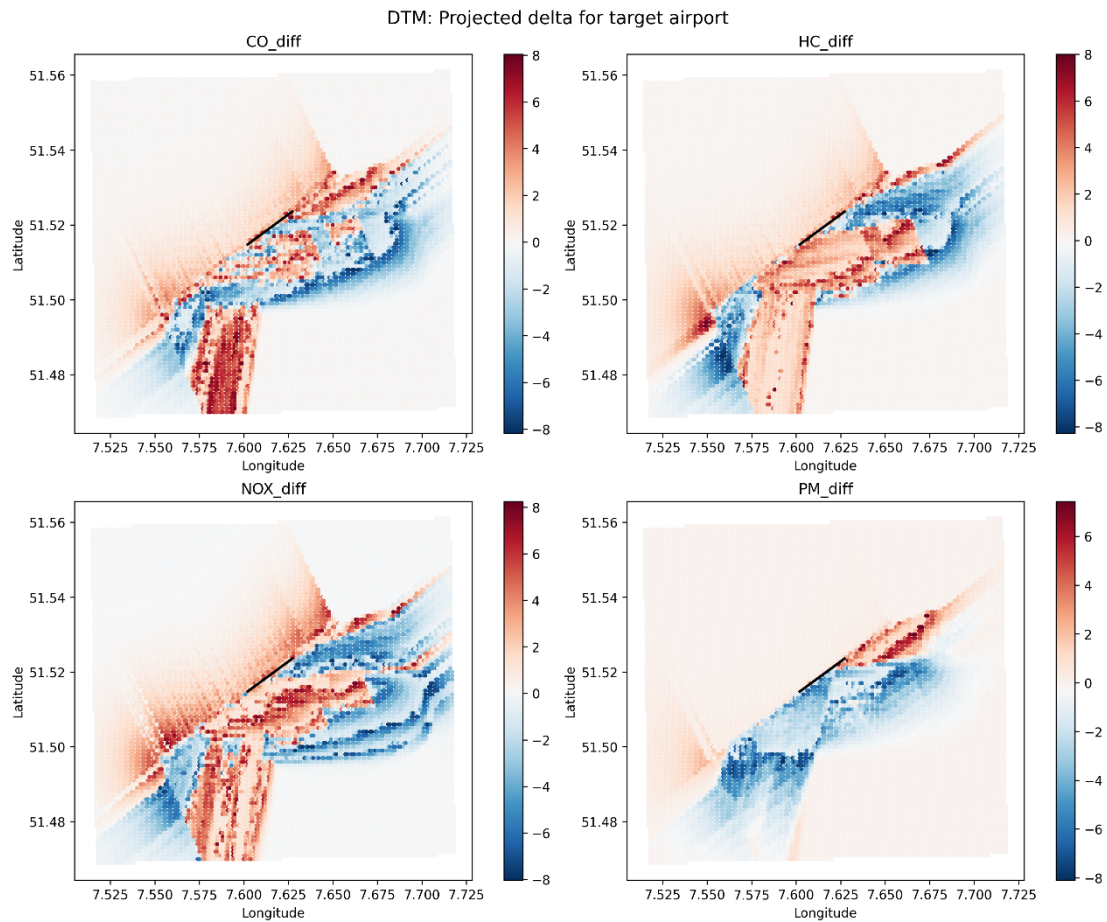


Figure 31. Deltas calculated at Dortmund (DTM) for each pollutant and receptor.

For each runway, its midpoint is used as the local origin. Each receptor is described by two coordinates: its position along the runway axis and its perpendicular distance from the runway axis. Both coordinates are normalised by runway length. This creates a common runway-based reference system in which equivalent locations can be compared between the reference runway and a target runway.

The reference delta grid is then interpolated onto the receptors of the target airport in this normalised reference system. Receptors located within the area covered by the reference pattern receive interpolated values. For receptors outside this area, the closest available reference value is used and then reduced exponentially as its distance from the reference pattern increases. This prevents the transferred effect from remaining constant beyond the range supported by the reference data.

When the target airport has more than one runway, such as LEMD (Madrid) and LEBL (Barcelona), the transfer is performed independently for each runway.



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Therefore, every receptor obtains one estimated concentration change for each runway.

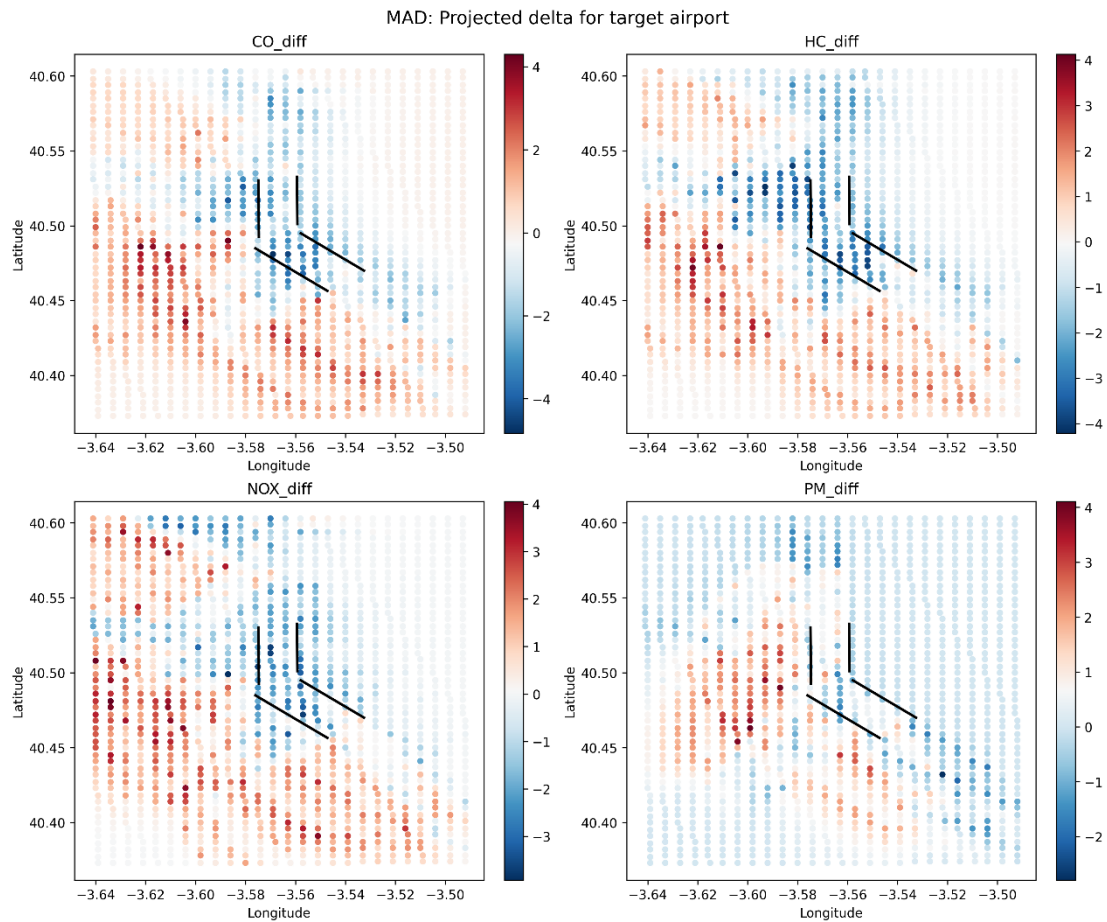


Figure 32. Deltas calculated at Madrid-Barajas (MAD) for each pollutant and receptor.

The individual runway contributions are then combined using the predefined runway weights to obtain the final delta grid.



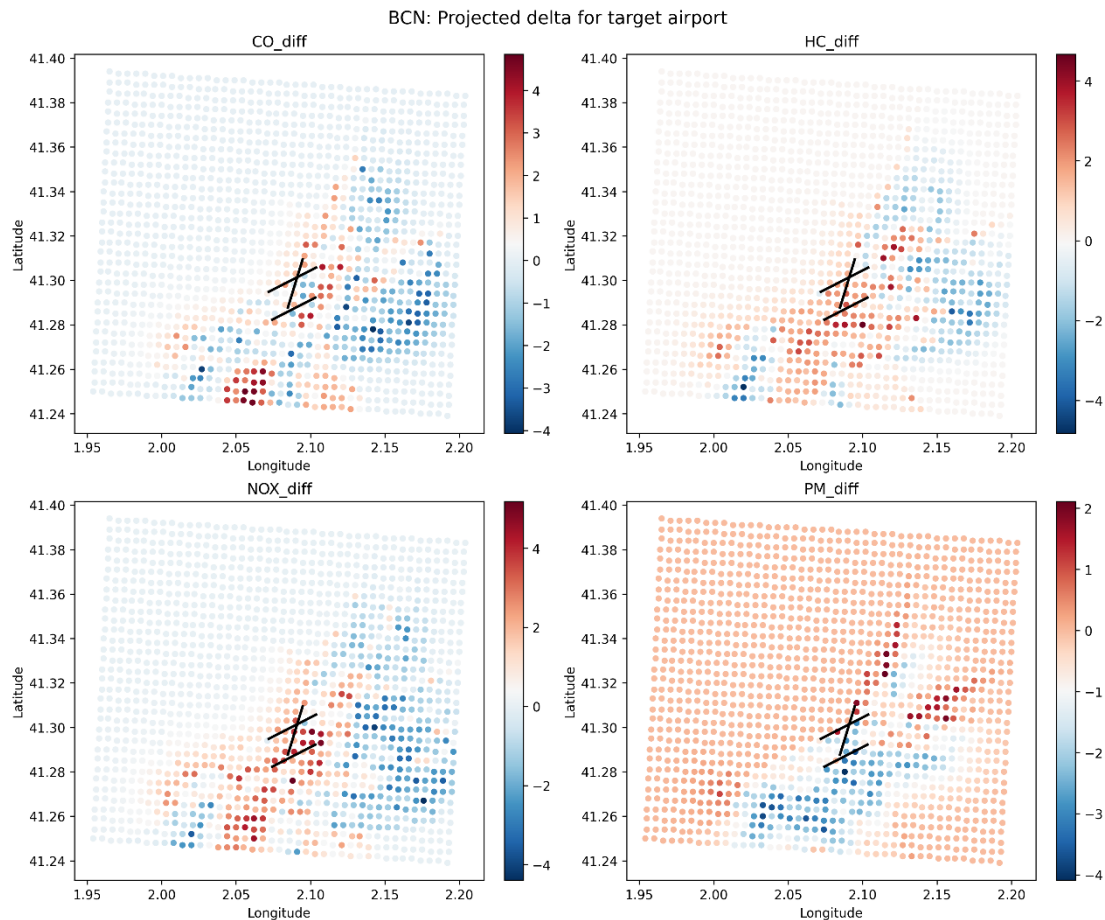


Figure 33. Deltas calculated at Barcelona-El Prat (BCN) for each pollutant and receptor.

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. RAZOR code generates a specific CSV file to add the corresponding deltas to each receptor based on these conditions.

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.



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x	y	avg_conc ($\mu\text{g}/\text{m}^3$)	zflag	grp	date	recep_idx	CO_diff ($\mu\text{g}/\text{m}^3$)	modified_conc ($\mu\text{g}/\text{m}^3$)
2112081,27	6630637,27	0,00009	1,5	F597	23082101	496	0,01204862	0,01213862
2112126,17	6630531,53	0,00009	1,5	F597	23082101	497	0,01204353	0,01213353
2112171,07	6630425,79	0,00008	1,5	F597	23082101	498	0,01204953	0,01212953
2110227,4	6635965,53	0,00036	1,5	F597	23082101	733	0,01211494	0,01247494
2112017,42	6631109,4	0,0001	1,5	F597	23082101	783	0,01197954	0,01207954
2110811,48	6634591,13	0,00022	1,5	F597	23082101	1040	0,01203912	0,01225912
2111825,66	6632525,7	0,00014	1,5	F597	23082101	1646	0,01261779	0,01275779
2111716,74	6633103,52	0,00016	1,5	F597	23082101	1932	0,01210319	0,01226319
2112038,44	6634114,02	0,00024	1,5	F597	23082101	3676	0,02560915	0,02584915
2117594,57	6623617,12	0,00003	1,5	F597	23082101	8170	0,02560567	0,02563567
2111651,11	6650058,99	0,00003	1,5	F597	23082101	18422	0,01253967	0,01256967
2112418,79	6648263,19	0,00026	1,5	F597	23082101	18733	0,02558452	0,02584452
2125970,03	6628562,35	0,00003	1,5	F597	23082101	35310	0,01210455	0,01213455

Table 3. Example of deltas applied to CO results in a PLT file.

All these results are aggregated and metrics and KPIs (average hourly concentrations, daily concentrations, etc.) calculated for the whole scenario. These results are also post-processed to calculate their derived impacts in economy and human health (deliverable D6.2).

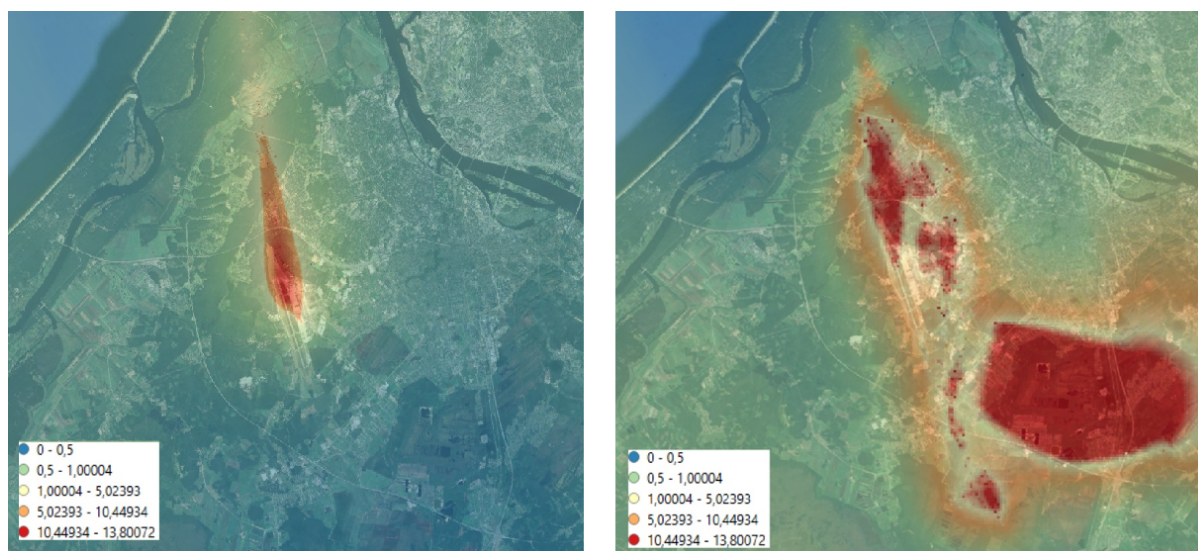


Figure 34. Comparison between initial resulted concentrations of CO ($\mu\text{g}/\text{m}^3$) (left) and concentrations after deltas application (right) at RIX.

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