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ESATTO: a holistic framework to support the design of sustainable supersonic and hypersonic civil aviation

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Abstract

The request for faster and greener high-speed civil aviation is urging the worldwide scientific community and aerospace industry to develop a new generation of supersonic and hypersonic aircraft, which are expected to be environmentally sustainable and to guarantee a high-level protection of citizens. To pursue this purpose, the H2020 MORE&LESS (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation), answering the EC call "Towards global environmental regulation of supersonic aviation" (LC-MG-1-15-2020), aims to support Europe in shaping global environmental regulations for future supersonic aviation. Specifically, the project aims to provide the Scientific Community with an integrated multi-disciplinary framework consisting of validated and accepted tools to holistically assess the environmental impact of supersonic airplanes on the future global air navigation system. This paper aims to describe the overall architecture of the ESATTO Framework "Environmentally Sustainable AircrafT Trajectory and Operations modelling Framework", as delivered at the end of the project. The ESATTO Framework integrates multiple specialized modules into a cohesive process for the design and assessment of environmentally sustainable supersonic aircraft. At a high level, the framework begins with a rapid aircraft modelling tool, which generates preliminary aircraft configurations and their propulsive and aerodynamic databases. These outputs feed into the environmental modules, which calculate emissions along representative flight trajectories and estimate their climate and atmospheric impacts. The framework concludes with an optimization stage that identifies the cruise altitude minimizing overall environmental effects. Each module exchanges well-defined input and output files, ensuring modularity and compatibility. The Remote Component Environment (RCE), an open-source software framework designed to support the integration, automation, and execution of complex workflows in distributed computing environments, is used to enable users executing ESATTO without requiring local installation of any components. When remote access to all the tools is available, the ESATTO Framework structure can be reproduced. ESATTO is developed to support the investigations of a wide range of supersonic and hypersonic aviation concepts, with different speeds, configurations, propulsion technologies and fuels. Specifically, this paper provides readers with a detailed description of the framework modular architecture, the development of the individual computational modules, and their integration within a distributed simulation environment designed to support the analysis of multiple high-speed vehicle configurations investigated within the MORE&LESS project, covering the Mach number range from 1.5 to 5.

Keywords: *Supersonic Aircraft, Hypersonic Aircraft, Multi-Disciplinary Design Optimization, Environmental Sustainability, Trajectory Optimization*

Nomenclature

AEDB – Aerodynamic Database

ASTRID-H 2.0 – Aircraft on-board Systems

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Sizing and Trade-off analysis in Initial Design – High-speed
CCD – Climb, Cruise and Descent
CO – Carbon monoxide emissions
CO_2 – Carbon dioxide emissions
CRN – Chemical Reactor Network
CS1 – Case Study 1 (Mach 2)
CS3 – Case Study 3 (Mach 5)
EDB – Emission Database
EI – Emission Index
FFM – Fuel flow emission estimation method
GHG – Green House Gases
H_2O – Water vapour emissions
HC – Unburned Hydrocarbons emissions
LTO – Landing and Take-Off cycle
MDAx – Multidisciplinary Design and Analysis Workflow Accelerator
MDO – Multi Design Optimization
MFC – Mass Flow Controller
MMTA – Multi-Mode Trajectory Analysis
NO_x – Nitrogen oxides emissions
OAC – OpenAirClim tool
P3-T3 – P3T3 emission estimation method
PDB – Propulsive Database
PSR – Perfectly Stirred Reactor
RF – Radiative Forcing
RCE – Remote Component Environment
SFC – Specific Fuel Consumption
SSeffect – Supersonic effect tool
SSFFM – Sustainable Supersonic Fuel flow emission estimation method
SSFFM – Supersonic Transportation
Y – Mass Fraction
ΔO_3 – Ozone column change

1. Introduction

In recent years, the aerospace sector has witnessed a renewed interest in civil supersonic and hypersonic transportation, driven by advances in materials, propulsion architectures, and the emergence of alternative fuels such as biofuels and liquid hydrogen. At the same time, growing environmental awareness and international regulatory efforts aimed at reducing emissions, noise, and sonic-boom exposure have highlighted the need for multidisciplinary and integrated design approaches that consider not only aircraft performance but also their environmental footprint throughout the operational lifecycle. Within this context, the H2020 MORE&LESS project (*MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation*), funded by the European Commission under the "Smart, Green & Integrated Transport" program, has developed the ESATTO Framework (*Environmentally Sustainable AircraT Trajectory and Operations modelling Framework*) [1]. The framework provides a unified methodological and computational environment capable of modelling, assessing, and optimizing the performance and environmental impact of future high-speed civil aircraft, covering a wide range of Mach number between Mach 1.5 and 5. The modular architecture of the framework is simplified by the block-diagram reported in Fig. 1.

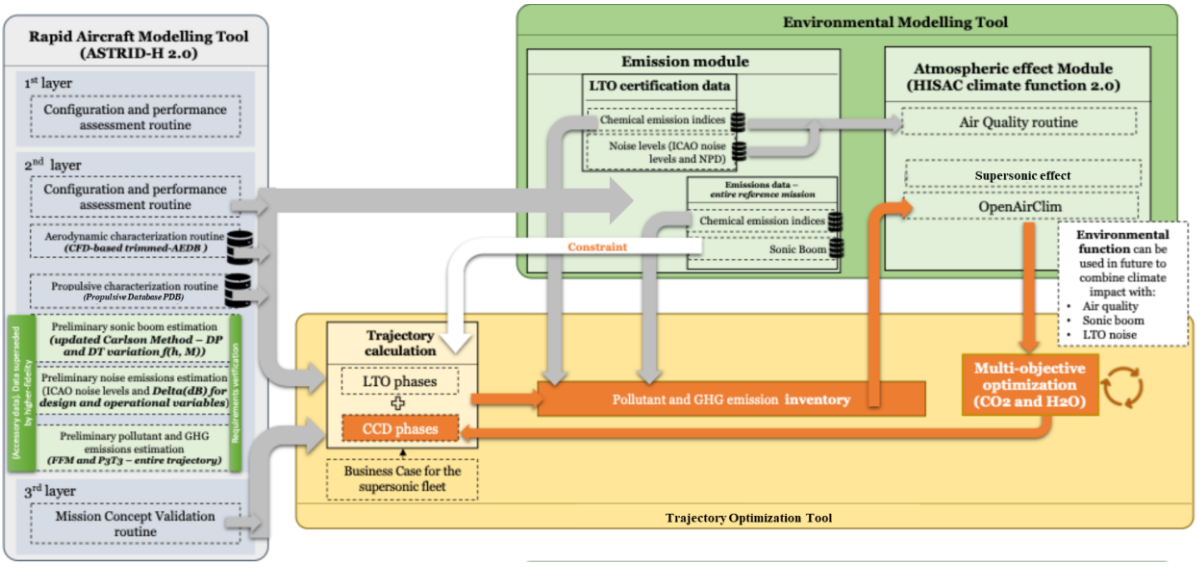


Fig 1. The ESATTO framework modular architecture

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ESATTO is designed as a multidisciplinary design and optimization (MDO) platform integrating three main blocks:

1. A **Rapid Aircraft and Mission Modelling Tool,** that embeds conceptual design methodologies and tools specifically developed to support high-speed transportation system [2][3]. This includes mission design capabilities [3][5]. By properly developing multi-fidelity aerodynamic and propulsive characterization routines, a novel framework has been established that enables mission simulations to be performed from the earliest stages of the design process and refined progressively throughout it. This framework provides a solid and exploitable foundation for the development of an innovative trajectory simulation and optimization routine.
2. An **Environmental Modelling Tool**, that integrates two subsequent modules. (i) The *Emission Analyses Module*, specifically developed to support Landing and Take-Off cycle (LTO) emission certification emulator, as well as to predict en-route emissions. In the last years, the research team have built robust capabilities in modelling engine cycles for high-speed applications, as well as in simulating 0D/1D chemical kinetic combustion processes with different fuels and atmospheric conditions [6][7]. Benefitting of the results of high-fidelity simulations and test campaigns, the combustion and emission routines have been duly validated. Then, (ii) an *Atmospheric and Climate Impact Module*, which allows assessing the impact on atmosphere and climate of supersonic fleets. The embedded routines originate from surrogate models derived from the high-fidelity atmospheric and climate response models explored during the project.
3. A **Trajectory Optimization Tool**. Building on the results of the sensitivity analyses of the atmospheric response, carried out for a fleet of high-speed aircraft operating along predefined reference routes and varying with the selected flight corridor, the trajectory optimization tool enables comprehensive parametric investigations to understand how modifications to the reference mission profile can contribute to minimizing the overall climate impact.

Through the coupling of these tools, ESATTO enables a continuous workflow from mission requirements to aircraft definition, and subsequently to environmental impact assessment and optimization of flight operations with respect to overall sustainability objectives. The following sections provide a detailed description of the framework architecture and its computational modules (Section 2), as well as their integration within a distributed simulation environment adopted for the case studies of the MORE&LESS project (Section 3). Finally, Section 4 presents concluding remarks on the applicability of the framework and its broader impact within the context of the eco-sustainable transition of the aerospace sector.

2. The ESATTO Framework - Methodology and Architecture

The ESATTO Framework integrates multiple specialized modules into a cohesive process for the design and assessment of environmentally sustainable high-speed aircraft. At a high level, the framework begins with the rapid aircraft modelling tool, which generates preliminary aircraft configurations and their propulsive and aerodynamic databases. These outputs feed into the environmental modules, which calculate emissions along representative flight trajectories and estimate their climate and atmospheric impacts. The framework concludes with an optimization stage that identifies the cruise altitude minimizing overall environmental effects. Each module exchanges well-defined input and output files, ensuring modularity and compatibility.

2.1. Rapid aircraft modelling module (ASTRID-H 2.0)

Among the framework modules, the ASTRID-H 2.0 tool plays a pivotal role. It generates the aircraft geometry, aerodynamic and propulsive databases, and preliminary environmental estimations that feed the downstream trajectory and environmental modules. Therefore, ASTRID-H must guarantee a robust balance between computational speed and physical accuracy, ensuring consistency and reliability of the

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databases used across the ESATTO workflow. This section provides a detailed description of the ASTRID-H 2.0 Rapid Aircraft Modelling Tool, its structure, modelling strategy, levels of fidelity, and role within the ESATTO Framework. ASTRID-H 2.0 (Aircraft on-board Systems Sizing and Trade-off analysis in Initial Design – High-speed) is an evolution of the ASTRID code originally developed at Politecnico di Torino for conceptual and preliminary aircraft design. The "H" release was conceived to extend ASTRID's capabilities to the supersonic and hypersonic regimes, addressing the MORE&LESS project requirement for a fast, flexible, and parametric modelling engine suitable for the conceptual design of high-speed civil aircraft powered by various propulsion systems and fuels.

The main technical objectives of ASTRID-H 2.0 are to:

- Automatically generate aircraft geometries and mass breakdowns for supersonic configurations.
- Build aerodynamic and propulsion databases consistent with different architectures and fuel types.
- Provide preliminary estimations of emissions and noise/sonic boom to support environmental modelling.
- Operate as the entry point of the ESATTO workflow, supplying harmonized input data for environmental impact assessment and trajectory optimization modules.

ASTRID-H 2.0 employs a three-layer architecture, as reported in Fig. 2, designed to combine fast turnaround times with progressively increasing physical fidelity. The first layer performs the initial conceptual design based on user-defined mission requirements (payload, range, cruise Mach number, fuel type) by using semi-empirical correlations (e.g., Raymer's formulations and the Breguet range equation). The tool computes the main aircraft geometry (fuselage length, wing area, tail surfaces), the take-off weight, the operating empty mass, and the fuel mass. A Matching Chart is then generated to identify a consistent operational point between thrust-to-weight ratio (T/W) and wing loading (W/S) for the selected mission. An iterative convergence loop updates weights, fuel fractions, and performance until mass and range requirements are simultaneously satisfied. In the second layer, ASTRID-H 2.0 replaces the low-fidelity aerodynamic and propulsion models with medium-to-high-fidelity surrogate models derived from CFD simulations and experimental results produced within the MORE&LESS project. These models, scaled to the current geometry, provide improved estimates of lift and drag coefficients C_L, C_D, specific fuel consumption (SFC), and thrust as functions of Mach number, altitude, and throttle setting. This hybrid approach maintains computational efficiency while achieving accuracy levels suitable for integrated Multi Design Optimization (MDO) workflows. Moreover, this layer incorporates analytical routines for fast environmental performance estimation. Sonic-boom predictions are obtained using an enhanced Carlson method combined with simplified Whitham propagation formulations; noise levels during take-off and landing (LTO) are estimated using empirical correlations. Pollutant and greenhouse-gas emissions (NO_x, CO_2, H_2O, etc.) are evaluated through analytical methods such as P3-T3, Boeing Fuel Flow Method 2, and the Sustainable Supersonic Fuel-Flow (SSFF) approach [8][11], calibrated against detailed 0D/1D combustion simulations. This layer also accounts for alternative fuels, specifically biofuels and liquid hydrogen, by adjusting fuel volume, density, tank placement, and mission energy balance. Finally, the third layer includes an interface with the commercial software ASTOS [12], which is used to perform preliminary feasibility assessments, formulation and validation of a reference missions based on high-fidelity mission analyses.

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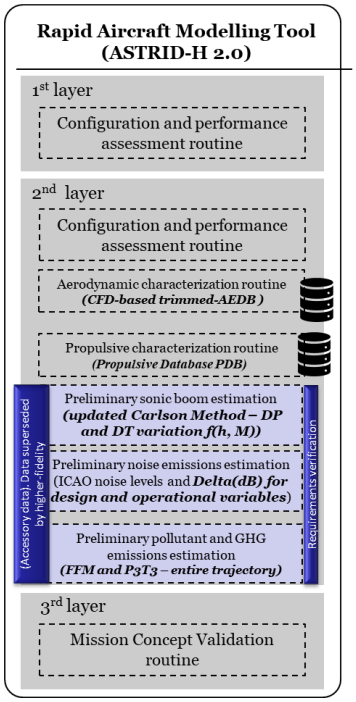


Fig 2. The ASTRID-H 2.0 three-layer architecture

This automated workflow ensures full interoperability and traceability within the ESATTO execution environment, i.e. the Remote Component Environment (RCE). The ASTRID-H 2.0 conceptual design tool has been applied to several supersonic to hypersonic case studies developed within the MORE&LESS project. The tool successfully reproduced aircraft geometry, mass distribution, and performance within a few seconds of runtime. Comparisons against higher-fidelity analyses and full mission simulations demonstrated agreement within 5–10 % for key performance indicators (MTOW, fuel mass, aerodynamic efficiency). These results validate its capability as a rapid conceptual modelling tool for parametric and sensitivity analyses in early-stage supersonic design. Within the ESATTO workflow, ASTRID-H 2.0 acts as the first executable module. Once the aircraft configuration and databases are generated, they are passed to the emission analyses routine for medium fidelity combustion simulations and pollutant estimation, and to the subsequent routines for environmental impact assessment and trajectory optimization. This ensures consistency among geometry, performance, and emissions, establishing ASTRID-H as the bridge between conceptual design and environmental analysis in the ESATTO chain.

2.2. Pollutants and GHGs Emissions Module

The Emission Module operationalizes a multi-tier combustion modelling strategy coupled with a chemical emission-estimation methodology, encapsulating them within a fully automated software component of the project design framework. The proposed multi-layer modelling approach integrates several chemical-kinetic simulation strategies to capture the intricate dynamics of combustion under varying operational conditions. Notably, the proposed modelling approaches leverage a single simulation suite, i.e. Cantera [13], to address the combustion phenomena. Upon selection of a case study by the user at the framework level, the Emission Module receives as input the associated propulsion database (PDB) - either generated upstream by the integrated ASTRID-H 2.0 module or directly provided by the user - and, without further user interaction, executes the emission analyses to produce a medium-fidelity Emission Database (EDB) in CSV format (easily convertible to Excel if required). These emission values are then processed downstream by the Emission Inventory Generator module, which integrates the EDB with mission-simulation waypoints to produce a georeferenced emission inventory for subsequent environmental-impact assessments, including climate-impact analysis and atmospheric response modelling. Upon receiving the PDB, the module executes the following automated modelling layers, summarized in Fig. 3:

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1. Equilibrium Baseline: Gibbs free-energy minimisation is first performed to yield rapid, equilibrium-based Emission Index (EI) and flame temperature estimates across the flight-envelope grid.
2. Finite-Rate Kinetics: Zero-dimensional Perfectly Stirred Reactor (PSR) and one-dimensional flame propagation solvers are then invoked to capture transient formation pathways, ensuring agreement with equilibrium flame temperatures while resolving time-dependent chemical-kinetic simulations.
3. Simplified Chemical Reactor Network (CRN): To balance fidelity and computational efficiency - particularly in hydrogen-fuelled, high-Mach scenarios - a reduced Chemical Reactor Network is constructed, interconnecting PSR and reservoir nodes via parameterised mass-flow valves.

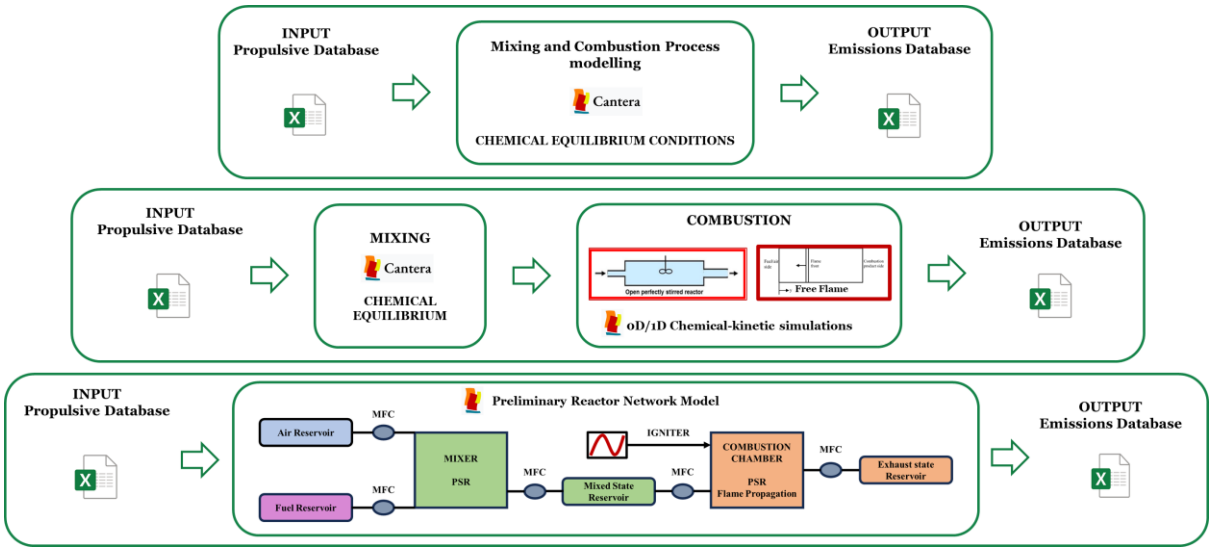


Fig 3. Combustion Simulations and Emission Analyses - cascading block diagram

All these thermodynamic and chemical-kinetic combustion simulations share a common Python executable, with automated parsing of fuel-specific chemical-kinetic mechanisms (e.g., HyChem A2_nox_skeletal for Jet A [14][15], HyChem C1_nox_skeletal for biofuel [16], z24_Nox [17][18] and CRECK-2012 [19] for hydrogen) imported via Cantera. This modular structure ensures the automatic handling of modelling tiers and kinetic mechanisms without further user intervention. Building upon the species-mass-fraction outputs from the most detailed and accurate modelling tier - the preliminary CRN - the module computes Emission Indices for each condition tabulated in the PDB using the formulation defined as in Eq. 1.

$$\mathrm{EI}_{\mathrm{emission}} = 1000 * \frac{\mathrm{Y}_{\mathrm{emissions\ outlet\ CC}}}{(\mathrm{Y}_{\mathrm{H_2\ inlet\ CC}} - \mathrm{Y}_{\mathrm{H_2\ outlet\ CC}})} \left[\frac{\mathrm{g}_{\mathrm{emissions}}}{\mathrm{kg}_{\mathrm{fuel\ burnt}}}\right] \quad (1)$$

Where Y denotes the mass fraction of fuel or pollutant species. For hydrocarbon fuels, CO_2, CO, HC, H_2O and NO_x are evaluated; for hydrogen, only H_2O, NO_x and unburned H_2 are considered. Outputs EDBs are saved as CSV tables, with each row corresponding to a unique operating-condition point. The Emission Module is encapsulated as a back-end Python component within the overall design framework. It operates without any direct user input once triggered by the framework execution pipeline. A configuration-driven pipeline orchestrates data ingestion, Cantera API calls, post-processing, and EDB assembly. Detailed logging ensures traceability of each simulation step, while the modular design supports straightforward extension to new fuels or kinetic mechanisms in future implementations.

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2.3. Emission Inventory Module

The Emission Inventory Module is a Python-based tool that maps engine emissions onto a flight trajectory to create a spatially and temporally resolved emission inventory. It takes as input a non-georeferenced Emission Database (EDB) generated by the ESATTO Emission Module. The EDB contains pollutant and greenhouse-gas emission indices (e.g. g of NO_x per kg fuel) tabulated over a grid of engine operating conditions (altitude, Mach number, fuel flow, thrust). Separately, reference mission profiles are computed using any flight analysis software (e.g. ASTOS), resulting in a 4D trajectory (time, latitude, longitude, altitude). Each point on the trajectory is associated with a corresponding fuel flow and thrust profile. The inventory module then cross-references each trajectory point with the nearest EDB grid conditions, multiplying the emission indices by the local fuel-burn to assign actual emissions at each point. In effect, this reproduces (at lower fidelity) what a full Multi-Mode Trajectory Analysis (MMTA) tool does: it generates a three-dimensional emission profile along the mission by multiplying engine emission coefficients by the fuel-flow history. For each time-step of the trajectory, the module looks up the corresponding EDB indices (given in g/kg fuel) and multiplies by the fuel consumption at that point to compute pollutant release. These pointwise emissions are georeferenced by the trajectory latitude/longitude and timestamp. The result is a flight-specific 4D emission inventory (emissions of each species at each location and time). Finally, the per-flight inventory is scaled by projected annual flight frequencies to obtain yearly inventories. For example, using documented projections for future supersonic and hypersonic operations [20] (37,500 flights/year for the CS1 Mach 2 configuration and 7,500 flights/year for the CS3 Mach 5), the module sums all flights to build an annual 4D emission inventory for each case. These annual inventories preserve latitude, longitude, altitude, and time of emissions. The full georeferenced inventory (4D emissions) is subsequently used for climate impact assessment, where the spatial and temporal pattern of emissions influences contrail formation and atmospheric chemistry. For atmospheric response (ozone) calculations, only the broad region and cruise altitude are needed. In practice, one may aggregate all cruise-phase emissions into corridor totals at the cruise altitude (neglecting precise geolocation) when using a fast stratospheric response tool. In this regard, the Emission Inventory module also serves to supply the Supersonic Effect tool with the inputs required to calculate the atmospheric response variation of a fleet of aircraft operating at different cruise altitudes. Specifically, the Emission Inventory module selects a subset of conditions tabulated in the EDB corresponding to various possible cruise-mach flight conditions at different altitudes. Based on the EI values tabulated for these conditions in the Emissive Database, the Emission Inventory module, in this case, is limited to estimating the total annual emissions for those cruise altitudes. This module thus bridges the engine-level emission data with flight trajectories, enabling subsequent environmental impact tools to work with spatially explicit inventories [21][22].

2.4. Environmental Impact Module

The Environmental Impact Module evaluates the climate and atmospheric effects of the flight emissions using two specialized software tools, both interfaced in Python.

- **OpenAirClim (OAC)**: A climate-chemistry response model developed by the German Aerospace Center (DLR) for the aviation industry. OAC takes as input the 4D annual emission inventory (with full latitude–longitude–altitude–time resolution) and computes global climate metrics. It does this by applying precomputed, non-linear response functions that emulate detailed climate-chemistry simulations [21]. OAC accounts for CO_2, NO_x/ozone, contrails, and other non-CO_2 species. Its outputs include Radiative Forcing (RF), surface temperature change, and other climate indicators. Key features are non-linear (tagging) treatment of NO_x chemistry, contrail cirrus formation (depending on fuel and conditions), and different CO_2/temperature models [21]. Because OAC uses a 4D inventory, it captures the regional and seasonal dependence of contrails and NO_x impacts (since non-CO_2 effects vary strongly with latitude, altitude and time). For example, aviation non-CO_2 forcings (especially contrails and NO_x-induced ozone) are sensitive to flight location and timing. In summary, OAC is a global climate impact calculator: it outputs the total or per-species climate impact (RF and temperature) given the full emission inventory specialized for a reference mission [21].
- **Supersonic Effects**: A Python package developed for quick estimates of stratospheric ozone and radiative impacts from SSTs. This tool does not require a full georeferenced inventory.

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Instead, it uses aggregated emissions over a chosen corridor (e.g. transatlantic) and a specified cruise altitude. Supersonic Effects employs empirical sensitivity data: ozone column change (in Dobson Units) and radiative forcing (in mW/m²) are computed as linear (with optional second-order Taylor expansion) functions of emissions at a given altitude and region [22]. Inputs to the tool are the total mass of emitted species (e.g. NO, SO_2, H_2O) per year, the flight corridor region (which sets the background atmosphere), and the cruise altitude. The model then interpolates known ozone and forcing sensitivities (based on 3D atmospheric simulations) to estimate the atmospheric response. Because it is very fast and explicitly altitude-dependent, Supersonic Effects is well suited for assessing how changing the cruise altitude affects stratospheric ozone depletion and radiative forcing. The outputs are ozone change (ΔO_3) and radiative forcing for the supersonic emissions at the given altitude and region [22][23].

OAC is comprehensive and global, it handles any aircraft fleet annual 4D inventory, including subsonic and supersonic flights, and produces long-term climate metrics. Supersonic Effects is specialized for SST corridors and ignores spatial details other than region and altitude. In ESATTO, OAC is used to quantify climate impact (through RF/temperature change), while Supersonic Effects provides a quick estimate of atmospheric composition impact (ozone depletion and short-term RF) of the supersonic cruise emissions. The contribution assessed via OAC is tied to the reference mission for which the Emission Inventory Module provides georeferenced emissions and hence cannot be parameterized as a function of cruise altitude - which is held fixed and constant for all flights over the course of a year. By contrast, the Supersonic Effect contribution is evaluated across multiple cruise-altitude conditions in a preselected range, for which emission rates are available from the EDB (expressed as a function of altitude, but not of latitude or longitude). Because Supersonic Effects evaluates atmospheric response with high sensitivity to cruise altitude, it is integrated into the design-optimization loop to rapidly identify the altitude adjustments that minimize ozone-variation impacts.

2.5. Optimization Process

The ESATTO optimization process employs the above-mentioned modules to identify the cruise altitude that minimizes overall environmental impact. Specifically, the state-of-the-art optimizer is implemented as a Python executable that: (i) inputs the key performance parameters from the impact analyses (climate impact and atmospheric response), (ii) superimposes these impact metrics and (iii) determines the cruise altitude at which their combined effect is minimized. In this selection, the contribution of the atmospheric response evaluated via the Supersonic Effect model is decisive. Indeed, the OAC (climate impact) contribution is assessed by adopting the reference mission derived from ASTOS-based feasibility studies, which assumes a fixed cruise altitude and uses georeferenced emissions from the Emission Inventory. Conversely, the Supersonic Effect contribution is computed for multiple distinct cruise altitudes, using propulsive parameters from the PDB and emission data from the EDB; the corresponding altitude-dependent atmospheric response is then calculated. For completeness, a future enhancement of the ESATTO optimization process will introduce an iterative loop to verify and ensure that, by adopting the cruise altitude identified by the optimizer based on Supersonic Effect results (atmospheric response), the revised mission indeed achieves the lowest overall impact, including climate effects (OAC). The planned optimization loop proceeds as follows:

1. Altitude selection: The optimizer picks a candidate cruise altitude (within feasible bounds). During the first iteration, the cruise altitude is determined by the reference mission profile derived from the ASTOS mission analyses.
2. Mission simulation: With that cruise altitude, ASTOS re-runs the mission analyses and checks feasibility (fuel, aircraft performance, flight path).
3. Inventory update: The flight trajectory from ASTOS is passed to the Emission Inventory Module (using the same EDB as before) to regenerate the georeferenced emissions. Because the EDB is trajectory-independent, only the trajectory changes, and emissions are recomputed for the new altitude profile.
4. Impact evaluation: The updated emissions feed into the Environmental Module. Climate impact: The annual 4D inventory is given to OpenAirClim, which calculates the radiative forcing and temperature effect. Atmospheric impact: The cruise-phase emissions (aggregated by species)

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are input to Supersonic Effects (for the selected altitude and corridor), which outputs ozone depletion and radiative forcing.

5. Objective computation: The overall environmental score (a combination of climate and ozone impacts) is computed.

This loop will repeat for different cruise altitude candidates, identifying at each iteration a new altitude that minimizes the atmospheric response, and subsequently evaluating its climate impact in the next loop to assess the combined environmental effect. At each iteration, the impact metrics update the objective function. Since previous studies have shown that cruise altitude strongly influences trade-offs between ozone and climate (lower altitudes reduce stratospheric ozone loss but can increase H_2O-induced warming), the optimizer ultimately identifies the altitude that yields the lowest combined impact. The process terminates when further altitude changes no longer improve (or worsen) the environmental score. The result is an environmentally optimal cruise profile: the feasible flight path that minimizes total climate warming and ozone perturbation according to the integrated assessment. Notably, even small altitude adjustments can have outsized effects on non-CO_2 impacts (as demonstrated in contrail studies) [23]. Therefore, incorporating a fine-grained altitude variable in the design loop is crucial. In the ESATTO framework, this optimization ensures that the final aircraft design operates at a cruise altitude chosen for environmental benefit, balancing aircraft performance with minimized atmospheric and climate effects.

3. ESATTO Framework implementation

To guarantee a transparent, repeatable, and collaborative workflow, the ESATTO Framework has been formalized and implemented using the Multidisciplinary Design and Analysis Workflow Accelerator (MDAx) and RCE environments, ensuring its operability across distributed computing infrastructures. The formalization phase was carried out within MDAx, a software environment developed by DLR to support multidisciplinary design optimization processes through modular and visual architecture. Within MDAx, each ESATTO module, such as the Rapid Aircraft Modelling Tool (ASTRID-H 2.0), the Emission Module, and the Environmental Impact Module, are represented as nodes connected through explicitly defined inputs, outputs, and dependencies. This formal representation enables full traceability of the data flow between modules, reproducibility of the optimization process, and straightforward adaptation or replacement of sub-modules (e.g., surrogate models or emission routines) as new data or models become available. Moreover, MDAx provides a graphical depiction of the optimization loop, highlighting the iterations between the environmental evaluation and the trajectory update cycle, which form the core of ESATTO's integrated logic. Following the formalization in MDAx, the operational implementation of ESATTO has been deployed within RCE (Remote Component Environment), an open-source framework also developed by DLR to enable distributed execution and automation of multidisciplinary workflows. RCE allows users to execute the entire ESATTO chain remotely and without local installation of the individual components. Each module is launched as a separate RCE component, connected through the standardized input–output structure defined in MDAx. During execution, the high-level input data are read by the input provider; ASTRID-H 2.0 generates the geometric, aerodynamic, and propulsion data, which are then automatically passed to the emission, inventory, environmental impact assessment and optimization routines. Finally, RCE manages the exchange of intermediate files such as the Propulsive Database, Emission Database, and Emission Inventory, ensuring a coordinated and error-free run of the entire workflow. This dual-level implementation, i.e. formalization in MDAx and execution in RCE, represents a key innovation of ESATTO. It not only enhances process transparency and reusability but also ensures that the complete framework can be shared, reproduced, and executed remotely by research institutions and regulatory bodies across Europe, thus supporting its long-term sustainability and dissemination beyond the MORE&LESS project.

3.1. Framework formalization

To ensure a clear and structured view of the framework operation, its formalization was carried out within the MDAx environment. MDAx [24] is a software platform designed to support multidisciplinary

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design processes in a modular and visual way, facilitating the integration of different tools into a single automated workflow. Its use enables clear definition of the connections between the various modules of the framework, specifying inputs, outputs, and logical dependencies. This structure ensures a more transparent, repeatable, and easily adaptable design process. Moreover, the graphical representation clearly shows the optimization cycle driven by the optimizer, highlighting the iterations between environmental evaluation and mission update. The formalization within MDAx also serves as a key step for the subsequent implementation and deployment of the framework on RCE, an environment that enables its remote and integrated execution. The ESATTO workflow has been formalized according to the schematic representation illustrated in Fig. 4.

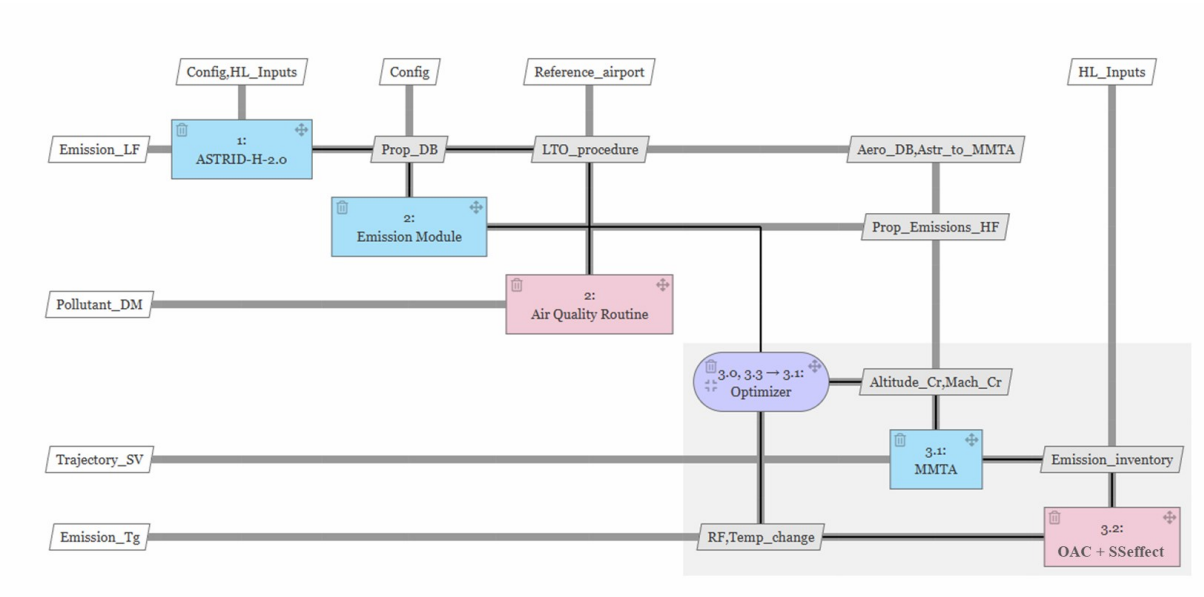


Fig 4. The ESATTO formalization - MDAx schematic

3.2. Framework integration

The ESATTO Framework is executed exploiting the RCE Environment [25][26], as reported in Fig.5. The first step about setting up the ESATTO Framework on RCE is to correctly configure the input provider by specifying the paths to the input files on the local machine. The ASTRID-H 2.0 tool is the first component to be executed, as it provides input data for both the Emission Module and the Inventory Generator Module. Specifically, the ASTRID-H 2.0 tool produces the Propulsive Database, which, through the Emission Module, is used to generate the Emission Database (EDB). The EDB is subsequently passed to the Emission Inventory Module and the Environmental Impact Assessment Module. The Inventory Module, using the reference mission also provided by ASTRID-H 2.0, generates an emission inventory containing georeferenced emissions along the reference flight path. Simultaneously, the Supersonic Effects tool supplies the optimizer with estimates of the annual atmospheric response for a fleet of case-study aircraft operating under different cruise-altitude conditions. In parallel, the OpenAirClim tool assesses the climate impact for the same fleet of aircraft, each assumed to follow the identical reference mission profile for which the Emission Inventory Module has generated the georeferenced annual emission inventory. Finally, the optimizer integrates the impact metrics obtained from OpenAirClim and Supersonic Effects at the reference cruise altitude, while determining the cruise altitude at which their combined effect is minimized. As a future development, an iterative optimization loop is envisaged. In the first iteration, the climate impact evaluated with OAC is associated solely with the user-provided reference mission and therefore reflects only a single, fixed cruise altitude condition. Subsequent iterations will update the reference mission to use the cruise altitude identified by the optimizer based on the Supersonic Effects atmospheric response minimization, and then re-evaluate both the georeferenced emissions inventory (Emission Inventory Module), the relative climate impacts of the same fleet of reference aircraft (OAC) and its overall impact (by superposing the atmospheric response contribution evaluated at the first iteration with Supersonic

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Effects). This loop will continue until convergence, thereby ensuring that the selected cruise altitude truly minimizes the overall environmental impact across both climate and atmospheric response metrics.

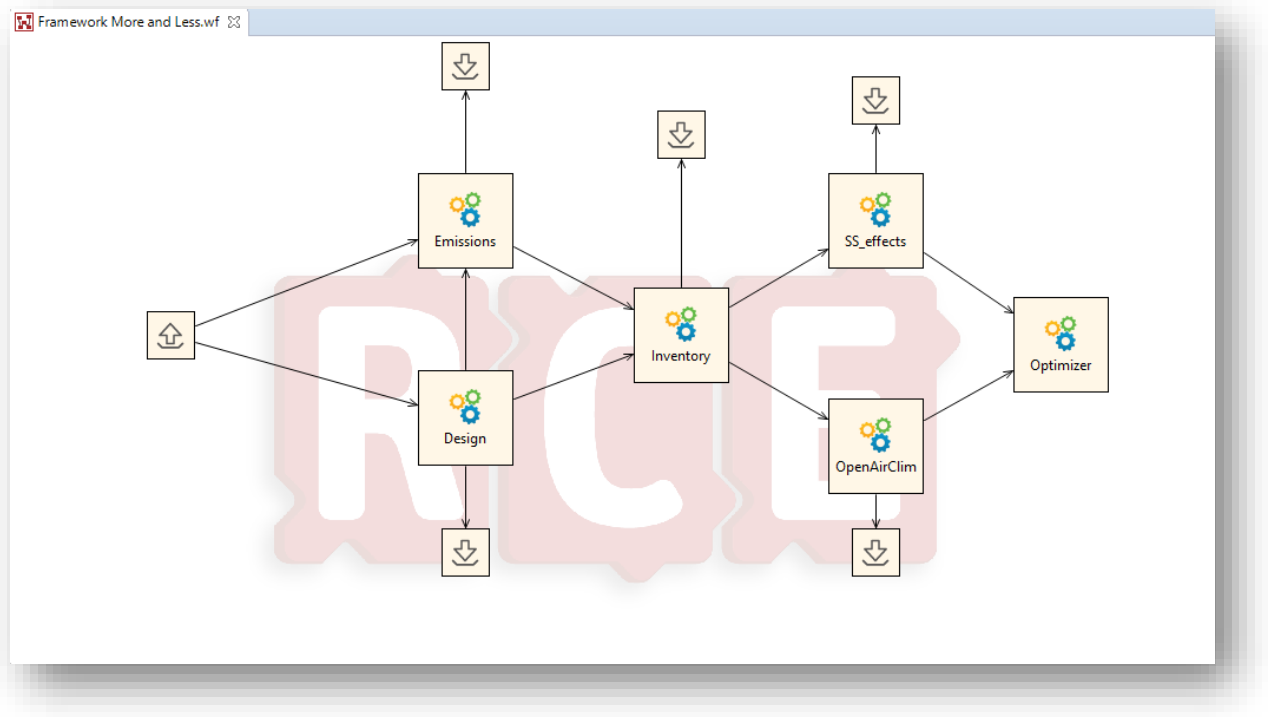


Fig 5. The ESATTO framework implementation in the Remote Component Environment

4. Conclusions

The ESATTO framework represents a novel, integrated multidisciplinary approach to high-speed aircraft design that simultaneously addresses performance and environmental objectives. Rather than treating design and environmental assessment as separate steps, ESATTO tightly couples conceptual aircraft modelling, mission simulation, and emissions calculation with climate and atmospheric impact analysis. In practice, rapid preliminary design outputs (vehicle configuration, propulsion and aerodynamic data) feed into environmental models that compute flight emissions and their impacts, and the process culminates in an optimization loop that selects flight conditions (notably cruise altitude) to minimize total environmental harm. The outcome is an environmentally-optimal flight profile that minimizes total climate warming and ozone perturbation according to the integrated assessment. This integrated loop ensures that even fine-grained design decisions are chosen to balance performance against atmospheric effects. Crucially, ESATTO is designed for broad application: it covers a Mach 1.5–5 speed range and accommodates diverse airframe configurations, propulsion systems and fuels, so it can guide many future supersonic and hypersonic concepts towards sustainability. By providing end-to-end environmental metrics during the design process, ESATTO has far-reaching implications for the aerospace sector transition to sustainable high-speed flight. It directly responds to the urgent demand for "faster and greener" aviation by embedding environmental impact in the conceptual design of next-generation supersonic aircraft. Such holistic assessments support the development of science-based regulations for supersonic aviation, giving regulators a rigorous basis for setting global standards. In this way, ESATTO helps ensure that advances in speed and efficiency do not come at the expense of planetary health. The scientific value of ESATTO lies in its multidisciplinary integration. By formalizing the data flow among all the considered disciplines, ESATTO makes the links between design choices and global environmental impacts explicit and traceable. This unified methodology is a significant advance: it transforms aircraft conceptual design into an environmentally-aware engineering process,

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rather than treating emissions as an a posteriori evaluation. The result is a design cycle in which early-stage decisions inherently consider long-term climate and ozone outcomes, thereby accelerating the development of truly sustainable high-speed aircraft. Looking forward, ESATTO provides a flexible platform for further enhancements. The modular architecture can readily incorporate additional physics or constraints. Extensions to the optimization could include economic or operational objectives alongside environmental ones, enabling multi-objective trade-off studies. Finally, scaling up the computational workflow, for instance by using surrogate models or high-performance computing, and validating predictions against high-fidelity simulations or flight tests will enhance robustness and efficiency. In sum, ESATTO establishes a comprehensive foundation for sustainable supersonic/hypersonic design, while future refinements will further expand its impact on high-speed aviation research and practice.

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