

SUPPORTING THE REGULATORY COMMUNITY SHAPING THE FUTURE OF SUSTAINABLE HIGH-SPEED CIVIL AVIATION: THE ESATTO FRAMEWORK

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Abstract

The renewed interest in commercial supersonic aviation has intensified the need for holistic methodologies capable of integrating environmental sustainability since the beginning of the design. Within this context, the H2020 MORE&LESS project developed ESATTO Framework (Environmentally Sustainable Aircraft Trajectory and Operations modelling), a multidisciplinary platform designed to support the development of future environmental regulations for supersonic transport. ESATTO integrates conceptual aircraft design, mission analysis, detailed propulsion and aerodynamic performance assessments, noise and sonic boom signature investigations, chemical emissions inventory generation, climate impact evaluation as well as the possibility to perform rajectory optimization to minimize environmental impact within a unified framework. The conceptual design module benefits from multi-fidelity surrogate models derived from extensive numerical simulations and experimental campaigns conducted during the project. Emissions inventories generated from aircraft along their trajectories are coupled with atmospheric and climate response models to quantify environmental impacts and support trajectory optimization. An optimization module identifies operational solutions that minimize climate effects while satisfying operational constraints. The framework is deployed through a Remote Component Environment (RCE), enabling distributed execution and accessibility. This paper presents the current architecture and capabilities of ESATTO and demonstrates its application to a Mach 2 supersonic airliner representative of a sustainable Concorde successor. Results highlight the potential of integrated multidisciplinary modelling and optimization to support environmentally responsible supersonic aviation and future regulatory decision-making.

1. INTRODUCTION

Over the last years, an increased worldwide attention and accelerated efforts towards the introduction of new commercial supersonic aircraft have been observed. At the same time, the International Civil Aviation Organisation (ICAO) Assembly Resolution Act A39-1 [1] instructs the Council to review its Annexes to ensure that they take due account of the problems that the operation of supersonic aircraft may create for the public. Furthermore, in 2018, Austria, on behalf of the European Union, its Member States, other Member States of the European Civil Aviation Conference, and EUROCONTROL presented a pivotal ICAO working paper [2] that addresses the environmental impact of civil supersonic aeroplane projects. On one side, the paper emphasizes the importance for the Regulatory Community, to develop stringent environmental standards, particularly regarding noise and emissions, before considering the integration of supersonic aircraft into the global air navigation system. On the other side, it calls for the development of methodologies and tools to support the definition of a consistent regulatory framework to ensure environmental friendly supersonic aeroplanes and public acceptability, bringing together noise pollution, sonic booms, CO2 emissions, and the climate impact of supersonic

flights.

In this context, in 2020, the European Commission published the call “Towards global environmental regulation of supersonic aviation” (LC-MG-1-15-2020), that aimed to address the challenge of contributing to help Europe shape high environmental standards, together with the International community, in line with ICAO Assembly Resolution A39-1, by performing a thorough and holistic analysis of the environmental impact of supersonic aviation, through basic and advanced research and experimental activities. The H2020 MORE&LESS [3] (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation) was one of the two international consortia funded under this call. The final objective of the H2020 MORE&LESS project, led by Politecnico di Torino and carried out by a team of experts belonging to well renown institutions, is to support Europe and international Regulatory entities to shape global environmental regulations for future supersonic aviation. The idea was to establish recommendations for the regulatory community based on the solid outcomes of extensive high-fidelity modelling activities, validated through test campaigns, whose results merge into a multi-disciplinary optimization framework, named ESATTO, (Environmentally Sustainable AircrafT Trajectory and Operations modelling Framework) to holistically assess the impact of supersonic aviation onto the environment.

This paper aims at disclosing the current set up of the ESATTO Framework, as it has been released at the end of the H2020 MORE&LESS project, together with the results obtained for a Mach 2 airliner (a remake of the historical Concorde with enhanced sustainability), which is hereafter used as a reference case study.

2. ESATTO FRAMEWORK

2.1 Framework Requirements

Before introducing the structure of the framework, it is fundamental to understand which have been the major requirements driving the definition of the functionalities to be embedded and consequently the overall layout of the framework.

First of all, ***the ESATTO Framework has been conceived to reproduce the variety of configuration and mission concepts pertaining supersonic aviation***. The H2020 MORE&LESS project investigated a set of meaningful real case-studies in the entire spectrum of supersonic speed regimes ranging from Mach 2 to Mach. Moreover, the analyses were not only restricted to aircraft using traditional hydrocarbon fuels, but it moves beyond, addressing aircraft concepts exploiting alternative fuels, such as bio-fuels and cryogenic fuels.

Moreover, in accordance with the relative EC call, ***the ESATTO Framework exploits accepted and/or validated software tools***. To achieve this goal, the various analytical, numerical, and experimental investigations carried out in MORE&LESS aim at upgrading and/or updating already available tools already developed and validated in previous EC projects, such as ASTRID-H [4,5] and HISAC [6,7], as well as proposing new validated routines to allow the future upgrade of internationally accepted tools such as IMPACT and AEDT.

Eventually, the ESATTO Framework has been developed with the aim to provide policy makers with scientific and technical evidence, thus contributing to shaping the future regulatory framework of upcoming generation of supersonic aviation.

2.2 The ESATTO Framework modules

As briefly summarized in Fig. 1, 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 the rapid aircraft modeling tool, which generates preliminary aircraft configurations [4,5] 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. However, the framework currently supports only supersonic flight scenarios with predefined fuel types and engine options and cannot simulate hypersonic liquid hydrogen configurations.

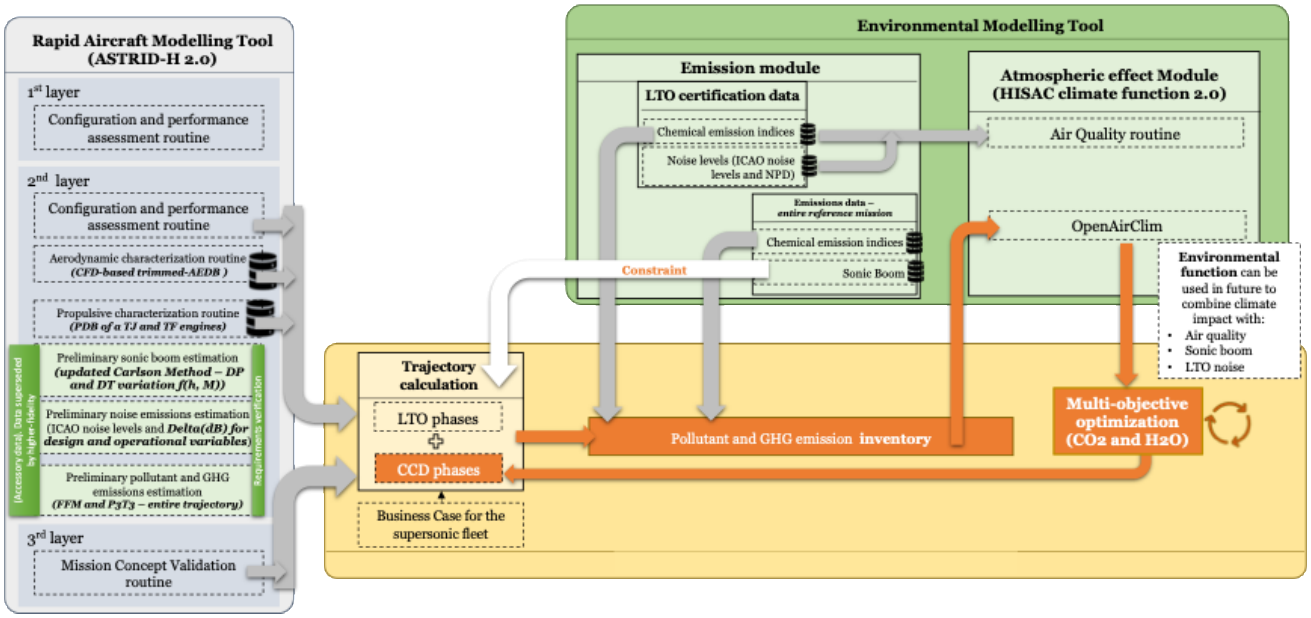


Figure 1 - ESATTO Framework conceptual view

In the following subsections, the three major bricks of the ESATTO Framework are described. the ESATTO. Framework currently consists of the following bricks:

2.2.1 Rapid aircraft and mission modelling tool

ASTRID-H 2.0 is a rapid aircraft modelling tool supporting the conceptual design of supersonic aircraft from low-supersonic regime (starting from Mach number equal to 1.5) to high-supersonic conditions (up to Mach number equal to 5). Considering the wide range of combinations for what concerns aircraft concepts in this field, with particular focus on types of configurations, propulsion plants and propellants, the tool features a modular structure allowing the user to properly run design exercises dedicated to the assessment of different case studies. The release of the software described in this work focuses on configurations of aircraft featuring a fuselage plus delta-wing layout (Concorde-like) and being potentially equipped with either turbojet or low by-pass ratio turbofan, powered by Sustainable Aviation Fuels (SAF) or hydrogen, stored in liquid state. Reference Mach number for these configurations is limited between Mach 1.5 and 3. The tool is capable of producing mass breakdowns, geometry data, thrust requirements, aerodynamic database, propulsive database, preliminary emissions database, preliminary sonic boom estimations, as well as initial noise estimations in Landing and Take-Off cycle (LTO). In order to do this, ASTRID-H 2.0 exploits a multi-fidelity analysis strategy, featuring a structure composed by three different layers to perform its analyses.

Firstly, a statistical analysis coupled with a low-fidelity algorithm produces an initial assessment of the aircraft starting from high-level requirements provided by the user (first layer). Then, once the first layer reaches convergence, the second layer updates the initial estimations by means of high-fidelity aerodynamic and propulsive surrogate models, developed directly from the case studies characterized in MORE&LESS which are used according to the aircraft variants considered for the run (second layer). Ultimately, the third layer provides the user with initial estimations of the environmental impact of the aircraft, preparing for subsequent steps of the overall workflow in ESATTO, which will lead to trajectory optimization by means of other modules.

The overall structure of ASTRID-H 2.0 is shown in Fig. 2 as schematic.

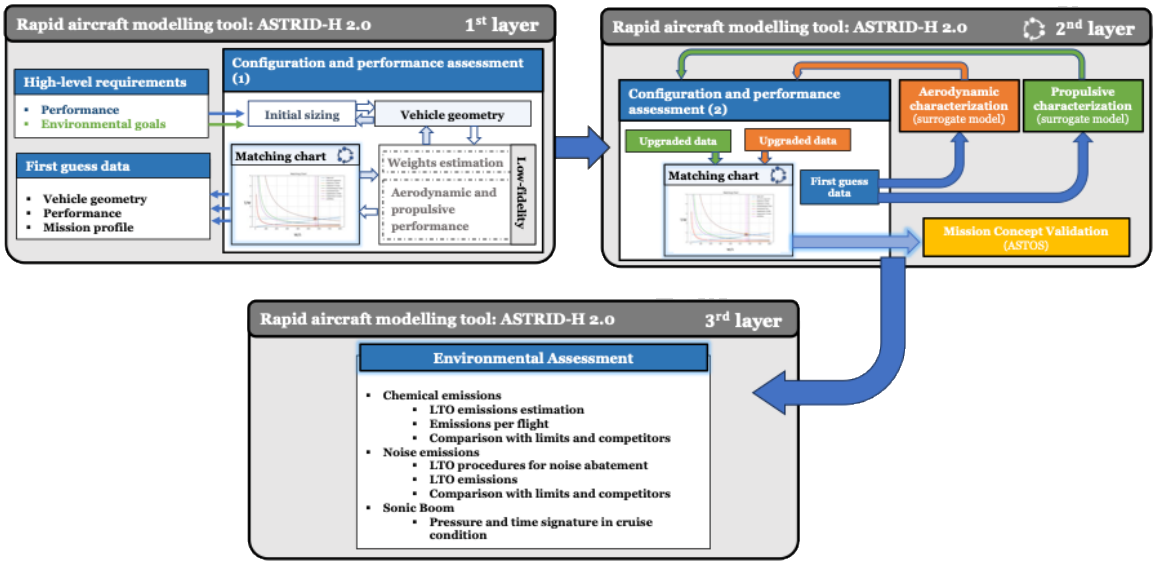


Figure 2 ASTRID-H 2.0 Layers organization

Notably, in the first layer, the tool implements a mathematical model inspired by [8], aiming at characterizing the mass breakdown of the aircraft iteratively, by analyzing the contributions to the empty mass and the fuel mass respectively. In order to do so, a simplified mission profile is sketched. Aero-propulsive characterization, which enables the computation of the overall breakdown, is performed following the prescriptions reported in [8], especially for what concerns aerodynamic coefficients prediction, with specific modifications in order to take into account the different aircraft category. In case a hydrogen-powered architecture is considered, the sizing of the reference tank volume, as well as its impact on aircraft layout and mass breakdown, is performed according to [9], in order to accounts also for structural and thermal management aspects. During the iteration, the tool also computes the thrust requirements along the different phases of the mission profile specified previously, exploiting the so-called matching chart, in which equilibrium conditions are translated into equations associating the thrust-to-weight ratios in the different conditions to the wing loading.
The second layer is conceptually similar to the first layer, since the same iteration is carried out, but the main difference is related to the adoption of surrogate models for the aero-propulsive characterization derived from high-fidelity simulations (e.g. CFD-based aerodynamic analyses and high-fidelity propulsion system simulations). The new data are thus integrated in the process, producing updates regarding mass breakdown as well as thrust requirements. The results of the first layer are used as initialization for the second layer in order to reduce the computational time.
The third layer exploits the results of the design loops in order to provide the users with preliminary environmental sustainability assessment. As far as chemical emissions concerns, analytical formulations, developed on the basis of the high-fidelity simulations carried out in the project, are used to update validated and accepted methods such as Fuel Flow Method and P3-T3 method to enable preliminary emission indices estimation [10]. Complementary, this layer implements an updated version of the Carlson Method [11,12] to allow the estimation of the sonic boom signature in terms of pressure and time signature for the under-development configuration.

2.2.2 The Emission module

The Emission Module operationalizes multitier combustion and emission-estimation methods, encapsulating them within a fully automated software component of the project design framework. The proposed multi-layer modeling 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:

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 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:** 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.

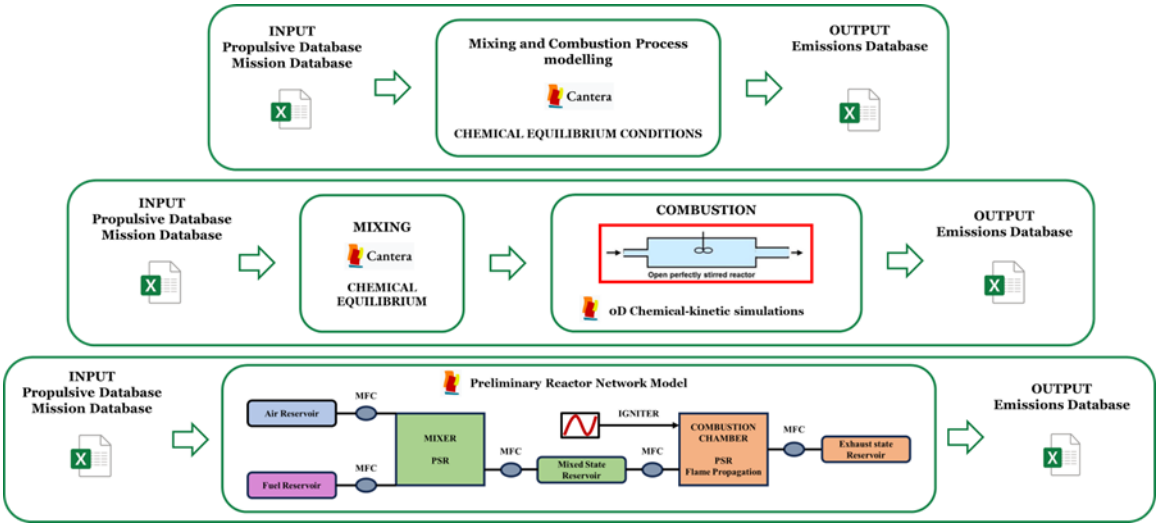


Figure 3 Combustion Simulations and Emission Analyses - cascading block diagram

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 [13], HyChem *C1_nox_skeletal* for biofuel [14], *z24_Nox* [15] and *CRECK-2012* [16] 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 For hydrocarbon fuels, CO_2, CO, HC, H_2O and NO_x are reported; 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; exporting to Excel (.xlsx) requires only minor script modifications.
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's 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.

2.2.3 The 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 [17]. 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's 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 [18] (37,500 flights/year for the CS1 configuration), 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. In the first iteration for CS1a, the plausible cruise altitudes range from 13 km to 18 km. Here again, an annual flight frequency can be estimated based on documented projections (37,500 flights/year for the CS1 configuration).

This module thus bridges the engine-level emission data with flight trajectories, enabling subsequent environmental impact tools to work with spatially explicit inventories [17,18,19].

2.2.4 The 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 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 (lookup tables) that emulate detailed climate-chemistry simulations [10]. 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. 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 [19].

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. 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 [20]. 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 [20,21]. OAC is comprehensive and global – it handles any aircraft fleet's 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 six equally spaced cruise-altitude conditions in the 13–18 km 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.

2.3 The ESATTO Framework formalization and execution

To ensure a clear and structured view of the framework's operation, its formalization was carried out within the MDAx (MDAO Workflow Design Accelerator) environment. MDAx [22] is a software platform designed to support multidisciplinary 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.

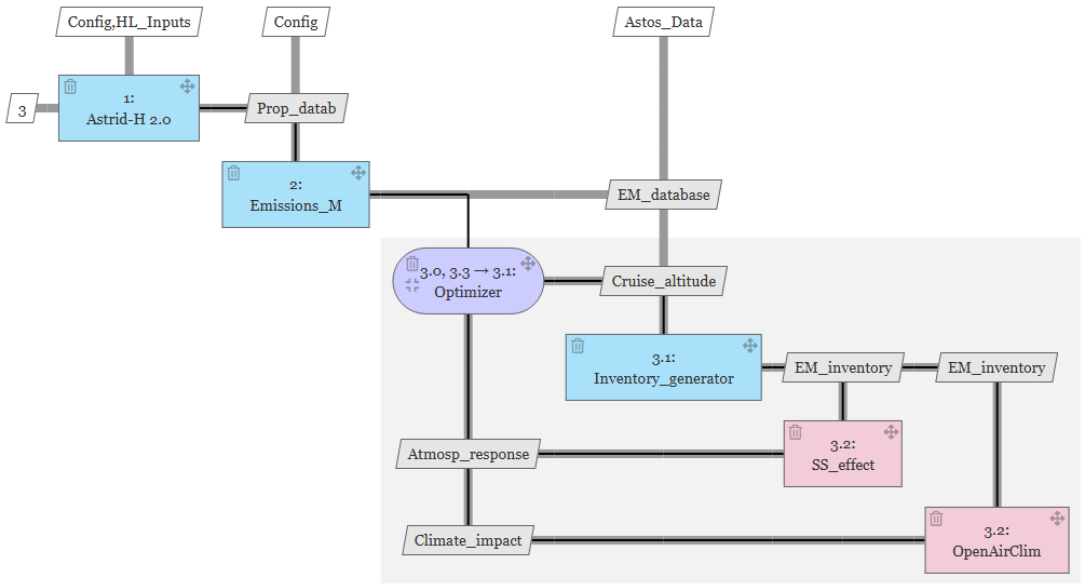


Figure 4 ESATTO Framework on MDAx

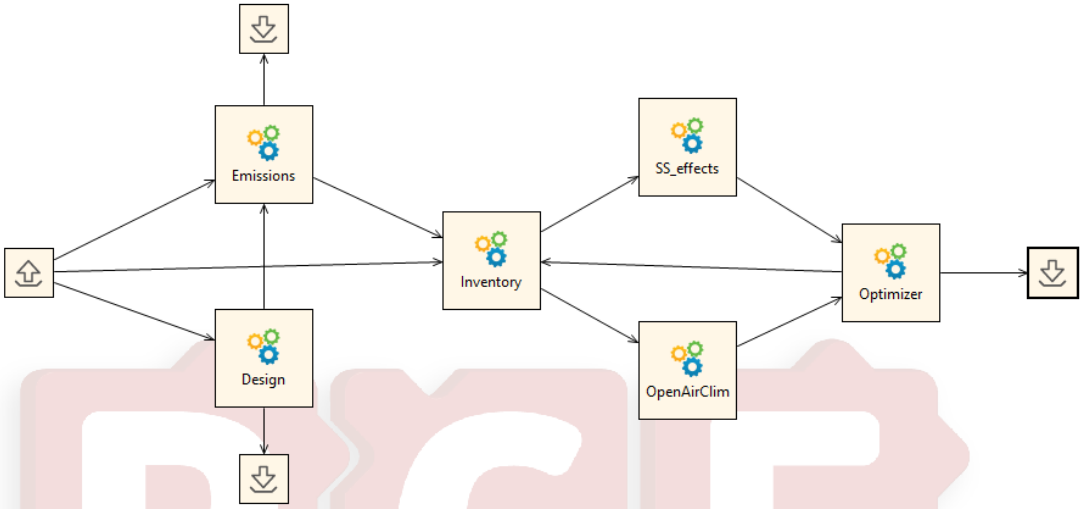


Figure 5 ESATTO Framework on RCE

The ESATTO Framework is executed exploiting the RCE Environment [23]
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 *Config.yaml, HLInputs_Mach2_Biofuel.yaml, HLInputs_Mach2_lH2.yaml and Reference_mission.xlsx* on your local machine.
The tool **Astrid-H 2.0** (labeled *Design* in the image) requires a connection to all three files, while for the **Emission Module** (labeled *Emissions* in the image), it is sufficient to connect only the configuration file.
The second input that must be connected to the EM is the Propulsive database (*Propulsive_database.xlsx*), which is generated as output by Astrid-H 2.0. Subsequently, the EDB produced by the Emission Module is passed to the Emission Inventory Module (labeled *Inventory* in the image) and to the Supersonic Effect tool (labeled *SS_effects* in the image). The inventory module, using also the reference mission provided by the input provider, generates an emission inventory containing georeferenced emissions along the reference flight path. Simultaneously, the Supersonic Effects tool provides the optimizer with evaluations of the annual atmospheric response from a fleet of case study aircraft associated with different cruise altitude conditions. In parallel, the OpenAirClim tool assesses the climate impact from the same fleet of aircraft - each aircraft assumed to follow the identical reference profile for which the Emission Inventory Module has produced the georeferenced annual emissions inventory. Finally, the optimizer superimposes the impact metrics resulting from OAC 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 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.

3. CASE STUDY

To demonstrate the functionalities of the ESATTO Framework and its capability of supporting the regulatory community shaping the future of sustainable high-speed civil aviation, this section shows the results of the application to a Mach 2 aircraft (CS1). This configuration is intended to be a redesign of the original Concorde with similar geometric and performance characteristics, featuring a cruise Mach number of 2.0 at an altitude of 59,000 ft. In particular, during the MORE&LESS project, a 3D CAD model has been built to reproduce the original Concorde geometry and to allow

for a complete aerodynamic characterization. Then, three different propulsive options have been investigated: the original Olympus turbojet engine, an upgraded turbojet engine and eventually a turbofan to reduce its environmental impact. Lastly, three different fuel options have been investigated: traditional kerosene, biofuel and hydrogen. In this section, the results obtained for the version equipped with turbofan engine and using drop-in fuels is reported.

The **Rapid Aircraft Modeling tool** is initiated with the minimum set of requirements reported in Table 1 to mimic the Concorde case study.

Table 1 Case study Input table

Description	**Value**	**Unit**
Passenger number	120	-
Weight per passenger including luggage	90	kg
Cruise Mach number	2	-
Range	6500	km
Specific Fuel Consumption	0.00003	kg/s/N
Number of engines	4	-
Maximum Take-Off field length	2500	m
Maximum Landing field length	4000	m

By selecting the design routine specifically developed for wing+body configurations, and indicating turbofan as key enabling propulsive technology, the tool provides a first geometrical description of the aircraft (see table 2). This set of data is necessary to apply the aerodynamic surrogate model that complements the geometrical description of the vehicle with a complete aerodynamic database (see Table 3). Complementary, benefitting of the numerical analysis carried out in the H2020 MORE&LESS, a turbofan database can be associated too (Table 4). All these elements are sufficient to draft a reference trajectory (see Table 5 and Figure 6).

Table 2 Conceptual Design Results

Description	**Value**	**Unit**
Maximum take-off mass	167690.04	kg
Operative empty mass	67312.34	kg
Fuel capacity	89277.69	kg
Airfoil maximum thickness ratio	0.03	-
Wing aspect ratio	1.62	-
Wingspan	23.79	m
Wing sweep angle	62.08	deg
Wing mean aerodynamic chord	19.02	m
Wing root	28.43	m
Wing taper ratio	0.06	-
Wing area	353.39	m^2
Tail aspect ratio	0.42	-
Tailspan	4.96	m
Tail sweep angle	60.71	deg
Tail mean aerodynamic chord	7.91	m
Tail root	11.29	m
Tail taper ratio	0.25	-
Tail area	58.79	m^2
Fuselage length	56.61	m

Engines number	4	-
W/S	474.52	kg/m²
T/W sub	0.40	-
T/W sup	0.48	-

Table 3 Extract from Aerodynamic database

Mach	Angle of Attach	CL_clean	CD_clean
0.95	-5	-0.19	0.02
1.05	30	1.21	0.69
1.6	15	0.58	0.15
0.95	10	0.58	0.1
1.2	15	0.72	0.19
0.3	5	0.22	0.02

Table 4 Extract from Propulsive database

Alt [m]	MN [-]	FN [kN]	WF [kg/s]	WA [kg/s]	SFC [g/kN/s]	BPR [-]	P_CC_in [kPa]	Tt_CC_in [K]	N_HPC [-]
0	0	144.36	2.37	296.45	16.44	1.30	1940	728	0.9
1100	0.4	112.00	2.33	283.09	20.82	1.24	1904	730	0.9
11,000	1	55.66	1.32	127.58	23.69	0.82	1054	713	0.9
13,000	2	54.84	1.71	190.30	31.14	1.18	1371	830	0.9
14,000	2	47.16	1.47	162.43	31.21	1.18	1172	831	0.9
15,000	2	40.59	1.27	138.64	31.30	1.19	1003	834	0.9
16,000	2	34.94	1.10	118.33	31.40	1.19	858	835	0.9
17,000	2	30.22	0.95	101.01	31.53	1.19	736	838	0.9
18,000	2	26.27	0.83	86.24	31.69	1.19	632	841	0.9

Table 5 Extract from Trajectory Analysis

Time [s]	Mach [-]	Altitude [km]	Latitude [deg]	Longitude [deg]	Propellant Mass [Mg]	Thrust [kN]	Mass Flow [kg/s]
0.00	0.35	0.00	49.01	2.54	82.19	487.18	10.01
106.61	0.52	1.20	49.06	2.34	81.13	437.55	9.66
1186.45	1.12	10.72	49.90	-1.25	73.79	269.54	6.69
1728.69	1.50	13.66	50.57	-4.11	70.26	220.87	6.07
2011.50	1.77	14.06	50.98	-5.88	68.24	276.26	8.11
2671.39	2.00	15.01	52.13	-11.01	63.32	225.05	6.95
7761.99	2.00	16.02	61.30	-57.32	31.44	181.42	5.63
11,250.00	2.00	16.68	67.58	-97.64	13.06	158.18	4.93

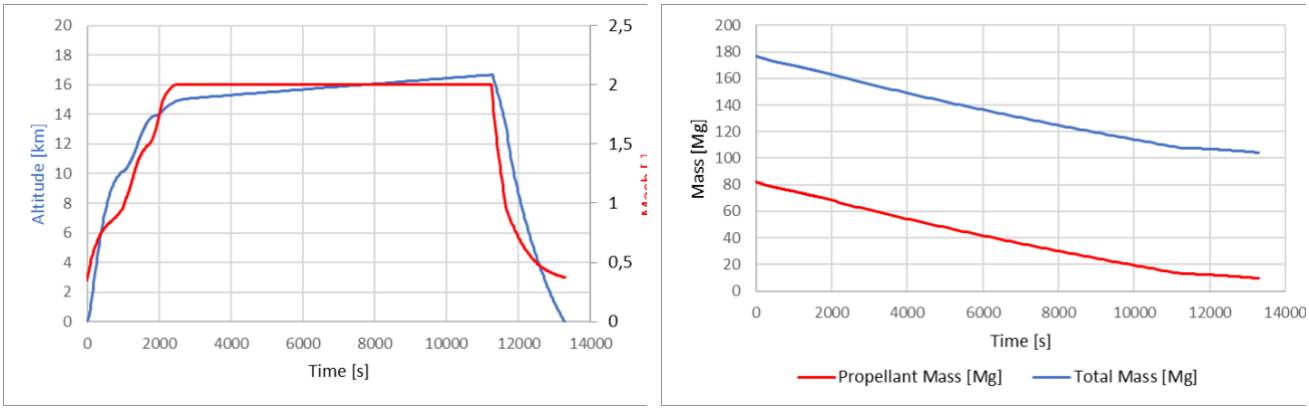


Figure 6 Mission profile details with Altitude and Mach vs. time (left), and with Propellant/Total Mass vs. time (right)

The outcomes of the Rapid Aircraft Modelling tool are then used by the Emission Module to elaborate the chemical emission database and eventually to compute the emission inventory along the reference trajectory.

Table 6 Emission Inventory

Alt [m]	MN [-]	EICO [g/kg]	EICO2 [g/kg]	EIHC [g/kg]	EINOx [g/kg]	EIH2O [g/kg]
0	0	4.33E+00	3.10E+03	8.57E-13	2.55E-01	1.37E+03
1100	0.4	1.75E-01	3.10E+03	1.45E-14	1.42E-01	1.37E+03
11,000	1	2.29E-01	3.10E+03	5.58E-22	1.75E-01	1.36E+03
13,000	2	4.95E-01	3.10E+03	9.82E-21	4.60E-01	1.36E+03
14,000	2	9.63E-01	3.10E+03	6.73E-20	1.01E+00	1.36E+03
15,000	2	1.96E+00	3.10E+03	5.57E-19	2.68E+00	1.36E+03
16,000	2	4.11E+00	3.10E+03	5.35E-18	8.18E+00	1.35E+03
17,000	2	8.98E+00	3.09E+03	6.34E-17	2.82E+01	1.34E+03
18,000	2	1.98E+01	3.07E+03	8.43E-16	9.98E+01	1.32E+03

The conditions in the EDB represent an engine operating grid (altitude, Mach), so the emission indices in the database are not georeferenced (i.e., they're not tied to any latitude or longitude). To feed the **Environmental-impact assessment tools** - both the climate-impact (OAC) tool and the Supersonic Effects tool - the framework uses the Emission Inventory module. This module performs three main tasks:

- **Georeference the EDB emissions** along the reference trajectory derived from the mission analyses, thereby constructing an emission inventory.
- **Select from the EDB** a subset of conditions representing possible engine operating points at different cruise altitudes.
- **Estimate the annual cumulative emissions** both along the reference mission and for the subset of cruise-condition points.

The resulting emission inventory is sent to the Climate Impact tool, while the cruise-condition dataset is forwarded to the Supersonic Effects tool. Below is an example of the Emission Inventory module's output.

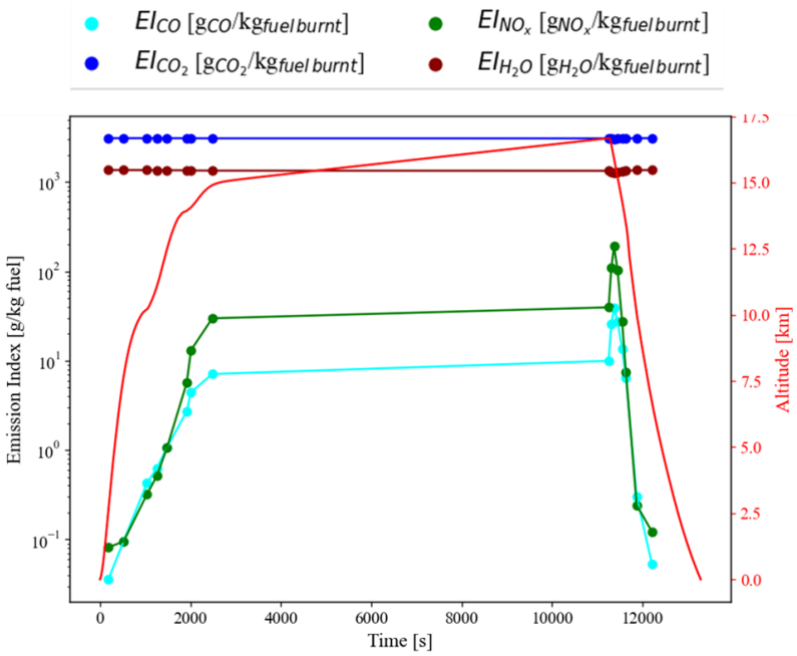


Figure 7 Mission Profile Emission Indexes/Altitude-Time

Table 7 Emissions/Year

alt [m]	NOx [Gg_NO2_eq/year]	H2O [Tg_H2O/year]
13,000	1.81	4.09
14,000	4.31	4.08
15,000	11.93	4.07
16,000	37.13	4.05
17,000	128.90	4.02
18,000	457.94	3.97

The atmospheric response is then computed with reference to the Transatlantic corridor, as shown hereafter.

Table 8 Atmospheric response

Alt [m]	NOx [Gg_NOx/year]	H2O [Tg_H2O/year]	Ozone [DU]	Radiative Forcing [mW/m^2]
13,000	1.81	4.09	0.00	0.40
14,000	4.31	4.08	0.00	0.50
15,000	11.93	4.07	0.02	0.79
16,000	37.13	4.05	0.07	1.75
17,000	128.90	4.02	0.15	5.69
18,000	457.94	3.97	0.07	20.13

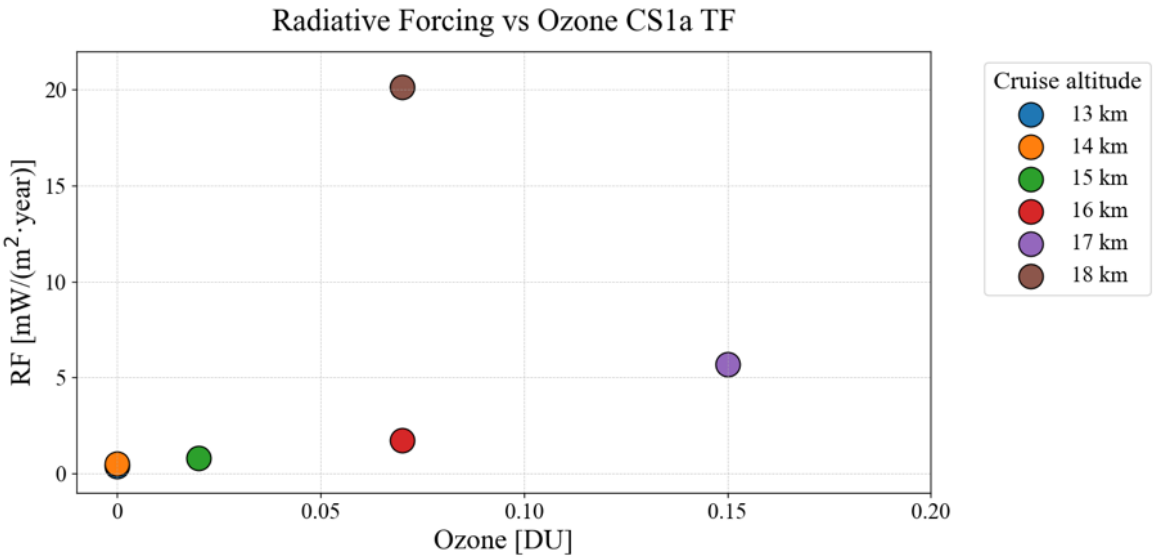


Figure 8 Radiative-forcing vs Ozone

Simultaneously with the atmospheric-response assessment performed by the Supersonic Effects tool, the framework also carries out an annual climate-impact evaluation for a CS1aMFTF fleet using the OpenAirClim tool. This tool ingests the georeferenced annual-emissions profile along the reference trajectory and quantifies the climate impact in terms of global-mean temperature change and radiative forcing, employing multiple metrics, as shown in the following results.

Table 9 Climate impact

	AGWP_1_2025 metric	**ATR_1_2025 metric**	**AGTP_1_2025 metric**
Chemical Species	**RF [W m-2 year-1]**	**ΔT [K]**	**ΔT [K]**
CO2	1.32E-05	1.00E-06	1.00E-06
H2O	1.06E-03	9.22E-05	9.22E-05
O3	2.34E-03	2.44E-04	2.44E-04
CH4	0.00E+00	0.00E+00	0.00E+00
contrails	3.38E-06	1.52E-07	1.52E-07
PMO	0.00E+00	0.00E+00	0.00E+00
total	3.41E-03	3.37E-04	3.37E-04

Downstream of this chain of modules and tools, a simple optimizer overlays the impacts evaluated by the Supersonic Effects and OAC tools to identify which of the candidate cruise altitudes probed by Supersonic Effects minimizes the atmospheric response. In the case of the CS1 Turbofan fed with drop-in fuels, these optimal cruise altitudes are 13–14 km - different from the cruise altitude assumed in the reference trajectory produced by the mission analyses.

Note, however, that this optimization minimizes only the atmospheric-response impact, not the overall impact that also includes climate effects. To ensure that the overall impact is minimized, the optimizer must feed the best-response cruise altitude back into a new trajectory optimization cycle. Once mission analyses verify the feasibility of the updated mission - now using the best-response cruise altitude identified in the first iteration - the loop of Emission Inventory → OpenAirClim & Supersonic Effects → Optimizer is repeated. At each iteration, the combined environmental impact is evaluated and compared with that of the previous iteration. This process continues until the best cruise altitude and hence the optimal trajectory that minimizes the overall impact are found.

4. CONCLUSION

The renewed interest in commercial supersonic aviation calls for the development of robust scientific methodologies and validated tools capable of supporting both technology developers and regulatory authorities in addressing the environmental challenges associated with future high-speed transport. In this context, the ESATTO Framework represents a significant step forward by integrating aircraft conceptual design, propulsion and aerodynamic performance assessment, emissions modelling, climate-impact evaluation, atmospheric-response analysis, and trajectory optimization within a unified holistic and multidisciplinary framework. The application to a Mach 2 supersonic airliner demonstrated the capability of the framework to quantify the environmental consequences of design and operational choices and to identify solutions that reduce their overall impact.

Beyond its technical capabilities, the main value of ESATTO lies in its potential to provide decision makers, policy makers, and regulatory entities with scientifically grounded evidence to support the definition of future environmental standards for supersonic aviation. As the international community moves toward the possible reintroduction of civil supersonic transport, regulations addressing emissions, climate impact, noise, sonic boom exposure, and operational procedures must be established on the basis of quantitative and transparent assessments rather than assumptions. Frameworks such as ESATTO enable the systematic comparison of alternative technologies, fuels, aircraft configurations, and operational concepts, thereby supporting the development of harmonized regulations that balance technological innovation, environmental protection, and public acceptance.

Future developments will focus on extending the optimization loop, increasing the fidelity of the environmental assessment modules, and broadening the range of aircraft concepts and propulsion technologies that can be analysed. In this way, ESATTO can evolve into a strategic decision-support platform for both industry and regulatory stakeholders, contributing to the establishment of a sustainable and environmentally responsible future for high-speed civil aviation.

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