HiSST: 4th International Conference on High-Speed Vehicle Science Technology

22 - 26 September 2025, Tours, France

CEAS
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Conceptual Configuration Design and Layout Optimization of an Supersonic Civil Aircraft

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Abstract

This research presents the development of a methodology for conceptual multidisciplinary design and optimization of supersonic civil aircraft, and the developed process is implemented within an automated aircraft design framework. The framework integrates low-fidelity and high-fidelity methods to address the unique challenges of supersonic transport, including aerodynamics, , propulsion, performance, and weight. Key features of the framework include a parametric geometry modeling tool, a surrogate optimization methodology, and a modular architecture for integrating multiple disciplines. A case study is conducted for the design of a Mach 1.6, 72-passenger aircraft with a range of 7,000 km. The aircraft configuration is developed using rapid engineering methods, area ruling requirements, and a modular optimization process. The subsonic emission analysis methodology is supplemented with methods for the estimation of emissions at supersonic speed. The results demonstrate the feasibility of the proposed design, with detailed aircraft characteristics and dimensions provided. Future work will focus on incorporating high-fidelity structural weight estimation, supersonic emission analysis, and sonic boom constraints to further enhance the framework's capabilities.

Keywords: Civil Aircraft, Supersonic Transport, Conceptual Design, MDO.

1. Introduction

Since the early 1970s and according to the Federal Aviation Administration regulations, the supersonic flight of civil aircraft over land has been prohibited due to noise issues. Despite this limitation, supersonic transport for civil purposes is being strongly investigated in academic and industrial sectors. There is a new wave of research from the beginning of the 21st century to address these issues, and to develop a feasible and profitable aircraft [1]. The supersonic transport will bring new potential to the transport market due to their higher speed, with a potential to be time-saving. This time-saving can benefit the business jet market [2]. On the other hand, for a successful entry into the market, the aircraft should be economically efficient and environmentally friendly.

In the conceptual design phase, different aircraft configurations are investigated. In this design phase, the configuration is so fluid that even the topology of the aircraft is allowed to change. For this reason, and to keep this agility and flexibility affordable, the fidelity of the aerodynamics and structural analysis tools is kept low [3]. Furthermore, the details that are considered in this phase are limited. But with the new requirements and considering the cost and emissions, it is important to develop tools and methods that are capable of design and optimization of aircraft with high-fidelity methods, even at the conceptual design phase.

On the other hand, the conceptual design and optimization of novel configurations require the integration of many disciplines (such as weight, aerodynamics, propulsion, performance, cost, emission, and noise) into a unified design framework. Depending on the configuration, the design framework should be capable of capturing the underlying physics of one or more disciplines, when no statistical or historical data is available. To overcome this issue, the design framework should be capable of both handling

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low-fidelity empirical and high-fidelity analysis tools [4].

In this research, an existing framework for subsonic and transonic civil aircraft conceptual design and optimization is extended to cover the design and optimization of high-speed supersonic civil aircraft. The framework is developed in MATLAB, and it compromises a modular architecture, which gives the potential for using different methods for each discipline. The developed framework is employed for the optimization of a Mach 1.6, 7000 km range, 72-passenger aircraft, to minimize aircraft weight, cost, emission, and noise. To this aim, the aircraft configuration is designed, and a base layout is developed using rapid engineering methods and area ruling requirements.

2. Requirements

2.1 Performance Requirements

The overall performance requirements are presented in table 1.

Table 1: Aircraft Top-Level Performance Requirements

Parameter	Value
Range	2700 [nm]
Cruise Speed	1.6
Number of Passengers	72

2.2 Mission Profile

Prior to the design of a supersonic jet, it is necessary to define the mission profile. In this study, the designed mission for the aircraft includes two subsonic cruise phases and one supersonic cruise phase, such that after the takeoff phase, the aircraft enters the climb phase and reaches the first subsonic cruise phase at an altitude of 11 [km]. Following the completion of the subsonic cruise phase, the aircraft climbs again to enter the supersonic cruise phase at an altitude of 20 [km]. The mission profile is illustrated in figure 1.

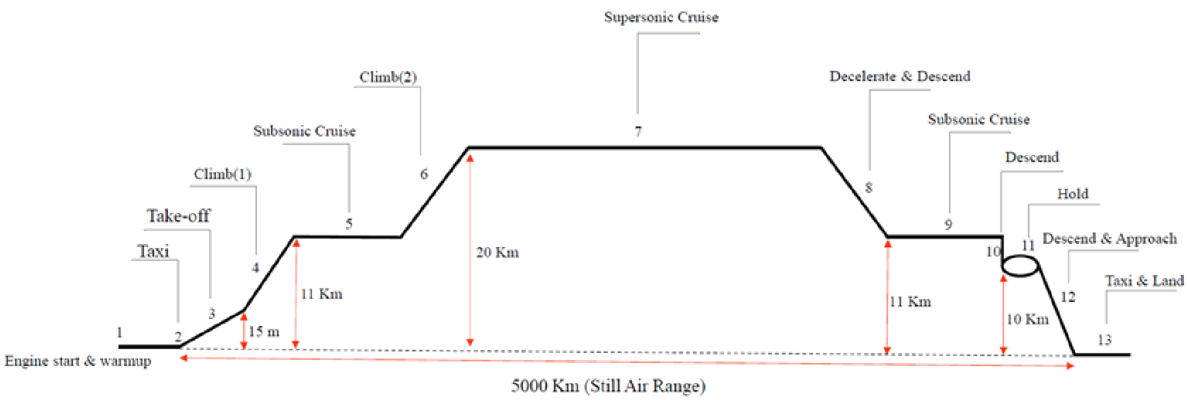

Figure 1: CaptionText

3. Methodology

3.1 Design Framework

For the design purpose, the LAMBDA (Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis) framework is used. The details of this framework are presented in [5], and a short introduction is presented here.

The need for an aircraft design framework existed from the beginning of the conceptual design of the TBW (Truss-Braced Wing) aircraft at AUT (Amirkabir University of Technology, aka Tehran Polytechnic) in 2010. Initially, spreadsheet tools, stand-alone scripts, and available software were used to perform the sizing, design, and sensitivity analyses. Later in 2015, there was a decision to use an integrated single framework for the design and optimization activities. After examining many of the existing tools, it was found that most of them lack the required flexibility to add new methods and tools. For this reason, decided to develop a new tool for aircraft design and optimization. For these reasons, the work on the development of LAMBDA started in 2015 with a focus on the design and optimization of the TBW configuration, and currently, the framework has progressed to a stage that performs essential aircraft design and optimization solutions for conventional and novel civil aircraft. LAMBDA is architected to be a multidisciplinary aircraft design and optimization framework, which has the capability of adding and using new methods of analysis or incorporating multiple levels of fidelity, without modifications to the core code.

The architecture consists of five layers (see figure 2). The user provides the primary input file, which may include links to custom methods and data that will override the default methods. The user interface has two primary duties: to process and validate the input files, and to prepare the output files according to the user requirements. The core engine module handles the data transfer between the internal modules and defines the sequence of their operation depending on the requested analysis. Internal modules are responsible for providing the required technical data, and they can employ internal methods or use one or many external tools. Each external tool has an interface module, which translates the data to/from the external tool. Outside of the framework, the required external tool should be available on the computing machine.

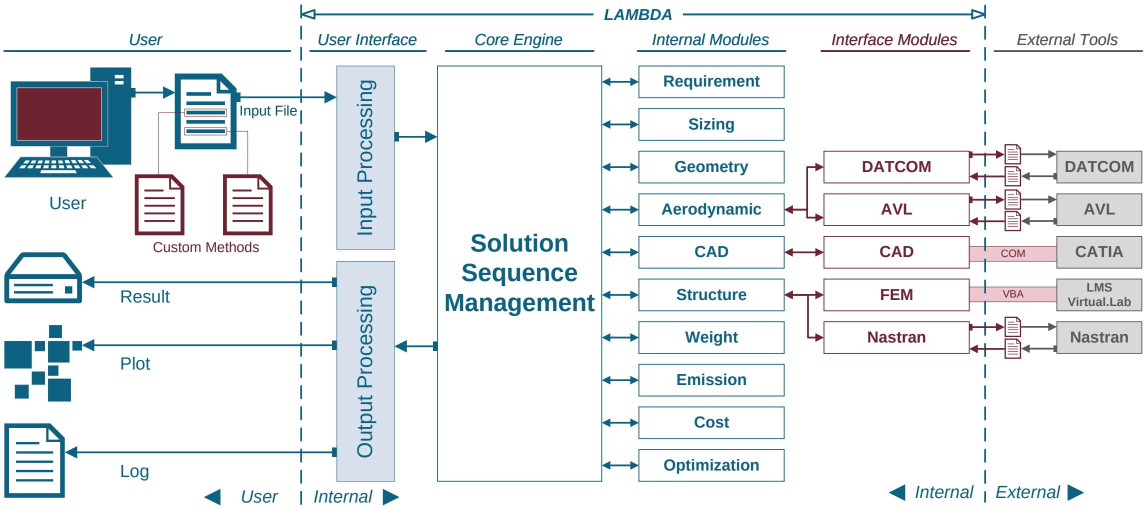

Figure 2: Framework Architecture [5]

The developed framework (see Fig 3) contains both statistical-based methods (empirical) and physics-based methods (low-fidelity and high-fidelity simulations). A set of codes is developed in MATLAB to transfer the data between the modules, iterate the convergence and optimization process, pre-processing the inputs, and post-processing the results. The code input is a text file, and its outputs are plots and the design results stored in local files. Since all required information, inputs, and options are defined inside the input file before the execution of the code, there would be no interaction with the user during the code processing. This file-based approach is selected over the interaction-based approach to reduce computational time and provide batch processing capability. The core disciplines of the optimization framework are Requirements, Weight, Sizing, Geometry, Aerodynamics, Engine, Performance, Cost, Emission, Noise, and Optimization.

3.2 Sizing

In order to determine the appropriate wing loading and thrust-to-weight ratio, the aircraft must be sized to provide a specific set of performance characteristics. Taking the process recommended by Roskam, the primary requirements typically resolved at the preliminary design phase are stall speed, take-off distance, landing distance, drag polar and climb constraints, cruise speed and rate of climb. These limitations are employed to offer safety, as well as operational convenience, in the different phases of flight.

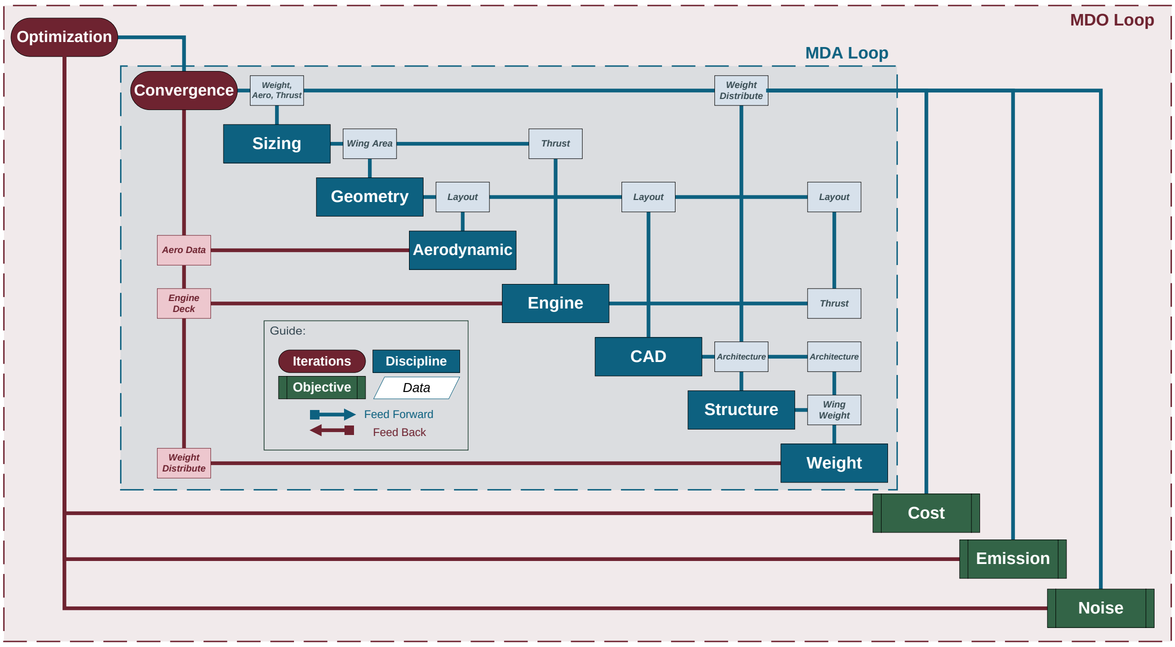

Figure 3: Optimization Framework Flow Chart

3.2.1 Stall Speed Constraint

For validation purpose, Concorde supersonic transport is assumed as the reference aircraft. Assuming consideration for stall speed requirement, wing loading is determined based on approach speed requirement. Based on the maximum lift coefficient in landing configuration ($C_{L_{max,landing}} = 1.31$) and approach speed of 164 [kt], the corresponding wing loading is determined as 105.7 [psf].

3.2.2 Take-off and Landing Constraints

A standard field length of 11 [kft] was assumed for take-off. The W/S to T/W ratio was computed for various assumed maximum take-off lift coefficients for developing constraint lines on the matching chart. At landing, the landing-to-take-off weight ratio was assumed to be 0.75 and $C_{L_{max,landing}} = 1.31$, which gives rise to the following corresponding wing loading of 84.61 [psf].

3.2.3 Rate of Climb Constraint

The climb performance requirement is evaluated at 250 [kt] reference speed typical of the initial climb after take-off. Using an assumed $L/D_{max} = 7.6$ for peak lift-to-drag ratio, the corresponding thrust-to-weight ratio works out to be approximately 0.29 [−] at 105 [psf].

3.2.4 Cruise Speed Constraint

For level cruise at Mach 1.6, at 80% of take-off weight, the lowest T/W for sustaining level flight is provided as the cruise constraint on the matching chart.

3.2.5 Matching Chart Result

Based on all the constraints, the selected design point is 0.4 thrust-to-weight ratio and wing loading of 105.76 lbs/ft2. Thus, the engine thrust required is 132,569 lbs and the wing area is 3,134 ft2.

3.3 Geometry

In this step, engineering methods are used to develop the geometrical layout where no input is provided by the user.

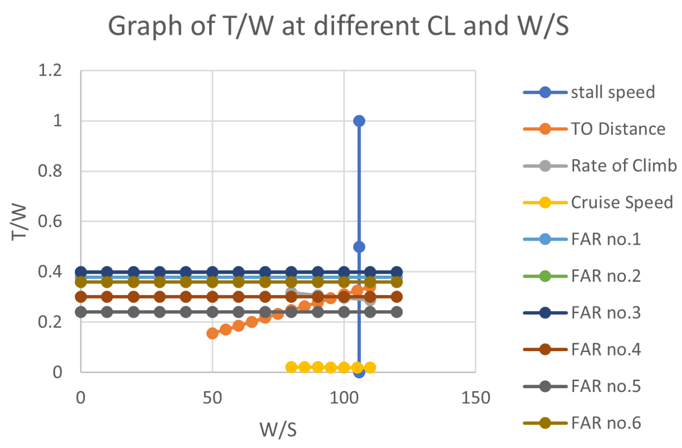

Figure 4: Matching Chart

3.3.1 Configuration

Based on the required thrust, the specifications of the selected engine, the mission requirements, and the analysis of supersonic aircraft configurations, the proposed initial configuration includes an aircraft with four engines, which will be positioned under the wings and close to the fuselage. Additionally, a conical and elongated fuselage with an elliptical cross-section has been utilized for this aircraft, with the fuselage dimensions calculated and determined using the method presented in aircraft design book. Furthermore, to enhance flight performance during the supersonic cruise phase, a delta wing configuration has been adopted, and to improve stability and controllability during the subsonic cruise phase, conventional horizontal and vertical tails will be used.

3.3.2 Fuselage

Based on the selected configuration and the method outlined in Roskam's book, the internal layout of the aircraft has been designed. Due to the elongated fuselage, additional space can be allocated for seat arrangement. The dimensions and sizes considered, based on Roskam's book and the fuselage dimensions, are presented in table 2.

The fuselage sizing is primarily based on the number of passengers. The number of passengers is used to determine the shape of the fuselage cross-section. The shape of the cross-section is assumed to be a complete circle, which will have less structural weight and an easier manufacturing process. Initially, the number of abreast is determined from similar aircraft. For the 72-passenger aircraft, four abreast with one aisle is selected. The upper range of the seat width, aisle width, and armrest width are used to determine the inner diameter. Based on the inner diameter and an inner-outer clearance, the outer diameter is computed. To compute the fuselage length, the fuselage is divided into three sections: nose, middle, and tail. A comfort seat pitch is selected, which is used to determine the seating zone length. With an addition to this length, which accounts for the galleys, lavatories, and doorways, the middle section length is computed. The lengths of the nose and tail sections are computed using assumed fineness ratios of 4.0 and 7.0, respectively.

The middle section is a simple cylinder, and the nose and tail sections are modified Von Kármán ogives. The Von Kármán ogive has the minimum pressure drag for a specified nose length, base area, and shape volume [6]. The fuselage layout is presented in figure 5, figure 6, and figure 7.

3.3.3 Wing

Several wing designs were experimented with and compared with successful supersonic transports' aerodynamic and flight behavior. Swept wings, similar to those used in subsonic and transonic transport airplanes, have superior low-speed performance and easier takeoff and landing. However, they have higher structural demand and higher wave drag in the supersonic regime compared to delta wings. Delta wing with canards, employed in the Tu-144, improves subsonic trim and longitudinal control but introduces additional complexity in design and excess drag at subsonic speeds.

Table 2: . Dimensions Considered for Fuselage Specifications

Parameter	Value
df (in)	140
lf/df	14.7321
lfc/df	6
θ_{fc} (degree)	2.7
lf (in)	2062.5
lfc (in)	840

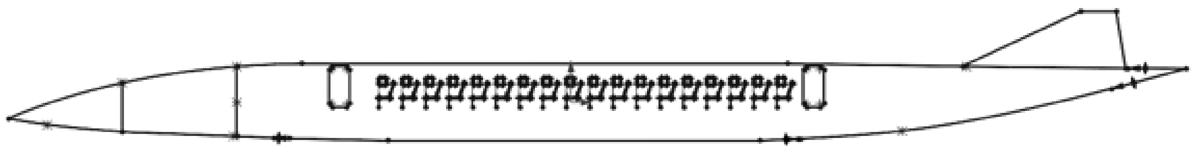

Figure 5: Side View of the Fuselage and Internal Layout

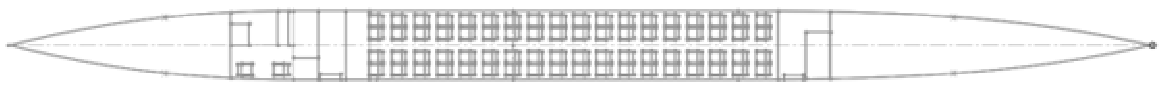

Figure 6: Top View of the Fuselage and Internal Layout

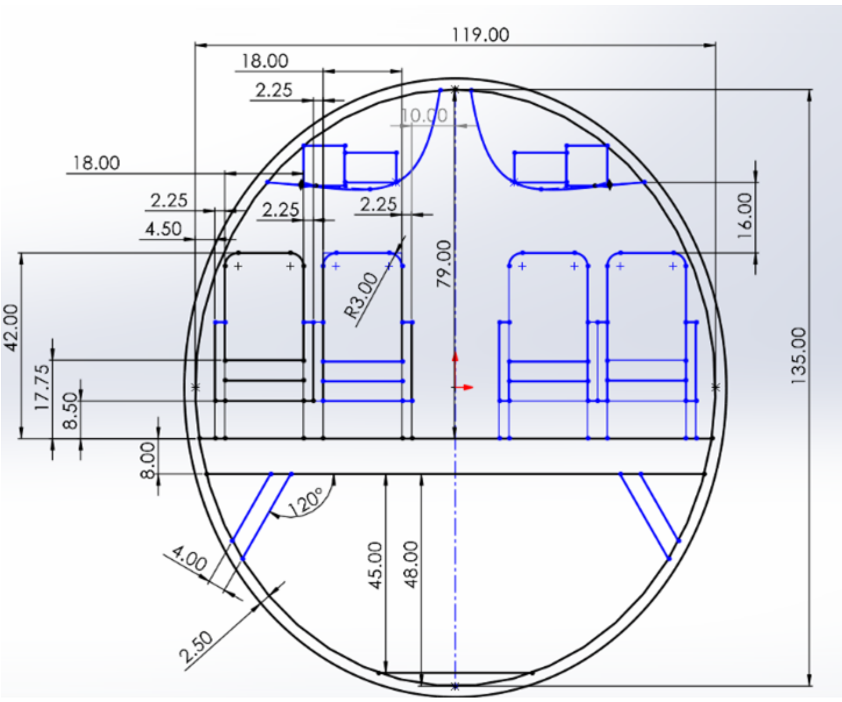

Figure 7: Cross-Section the Fuselage and Internal Layout

In response to these compromises, the present configuration adopts a matured ogival delta wing planform, quite similar to that of the Concorde. This planform provides excellent supersonic flight capability by maintaining low wave drag at Mach numbers above 1.5, while at the same time offering structural simplicity, internal fuel storage volume, and provision for under-wing mounting of engines. Furthermore, small retracting canards are also being considered for inclusion in order to enable improved control upon takeoff and landing, thereby addressing one of the disadvantages of the all-delta planform.

The c/4 quarter-chord distance from the leading edge of the wing to the nose was also quantified in other similar supersonic aircraft using specific software. From this analysis and comparison with existing designs, a figure of 30 meters was selected for the present aircraft. This placement is optimal for longitudinal balance and center-of-gravity control, which helps in stable aerodynamic performance along the flight envelope.

Table 3

Aircraft	Distance (m)	λ	Sweep
Concorde	34.05	0.145	ogival
Aerion AS2	28.63	0.58	-
Tu-144	41.32	0.125	76.57°
XB-70A		0.02	65.6°(LE)
Present Design	30.00	0.2	ogival

In the case of the ogival delta wing, a thickness-to-chord ratio (t/c) of 3–4% was employed. With such conditions, thin cambered ogival and symmetric biconvex airfoils are both the ideal picks for the design of the wing. As per Roskam's computation, the mean aerodynamic center turns out to be approximately 11 meters, giving the aircraft longitudinal stability and aerodynamic balance as needed.

3.3.4 Tails

The sizing of the horizontal and vertical tails is done using the tail volume method. Based on the data provided by Roskam for supersonic aircraft [7], 0.5 and 0.06 are selected for the volume coefficient of the horizontal tail and vertical tail, respectively. The planform of the tails is not changed during the optimization process, and it is only scaled using the computed area. Symmetrical NACA series 6 airfoil with a thickness ratio of 3% is used for both horizontal and vertical tails. The tails are equipped with control surfaces, namely elevator and rudder, with a chord ratio of 30%.

3.4 Aerodynamic

The aerodynamic lift and drag characteristics are required for sizing and performance analysis. To this aim, many options are available, ranging from quick handbook methods to high-fidelity CFD (Computational Fluid Dynamics) simulations. For supersonic and transonic flows, methods based on the "Linear Theory" are widely used in the conceptual design phase. Though these methods are simple to implement, provide good predictions when compared to CFD analyses [8]. The subsonic aerodynamic characteristics are computed using the build-up method [9]. The supersonic wave drag is computed using the supersonic area rule:

$$C_{D_{WV}} = \frac{1}{2\pi S}\int_0^{2\pi} C_{D_{WV_\theta}} d\theta \tag{1}$$

where

$$C_{D_{WV_\theta}} = -\frac{1}{2\pi}\int_0^l \int_0^l S''(x_1,\theta)\, S''(x_2,\theta) \ln|x_2 - x_1| dx_1 dx_2 \tag{2}$$

3.5 Propulsion

The `Engine` module prepares the thrust and SFC (Specific Fuel Consumption) values in the whole flight envelope. Three approaches are available for generating the engine performance charts: (1) **Direct Input**: The engine data are tabulated in text files, and the addresses of these files are added to the input file. (2) **Engine Scaling**: The "rubber engine" concept [10] is incorporated, and the thrust and SFC are scaled from a baseline engine. (3) **Engine Sizing**: The engine cycle is sized to the required thrust and the pre-defined top-level technological requirements of the engine, such as BPR (Bypass Ratio), OPR (Overall Pressure Ratio), and TIT (Turbine Inlet Temperature) [11, 12]. The results of engine sizing are used for the off-design analysis, and the variation of SFC and thrust versus Mach number and altitude are evaluated [13]; see figure 8.

In this research, the rubber engine concept is used.

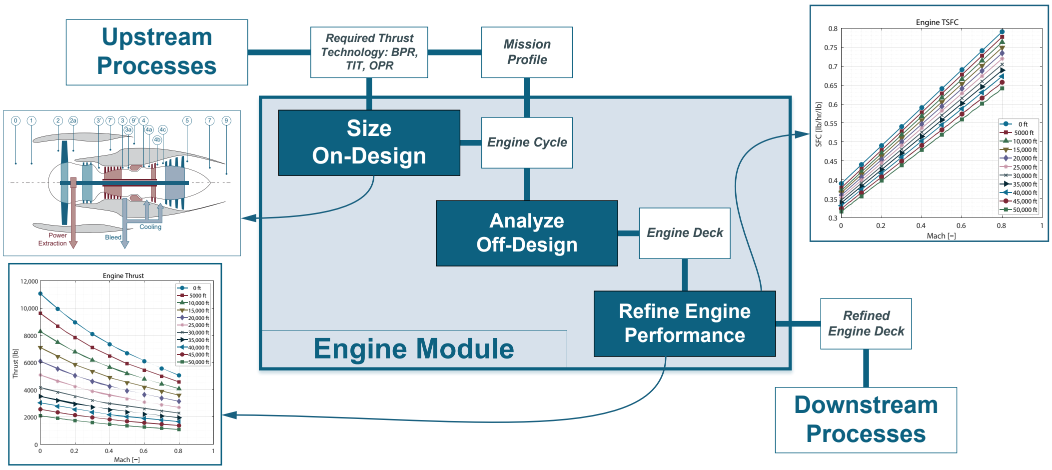

Figure 8: Engine Module Process

To estimate the thrust required for the new supersonic transport, a comparative approach was applied based on comparing existing aircraft of similar configuration and class of performance. Comparative vehicles applied include Concorde, Tupolev Tu-144, and the Boom Overture conceptual design. For this calculation, the total thrust required for the present design is approximately 132,500 lbf.

The Boom Overture engine is selected as the basis engine. The engine delivers 30,000-40,000 lbf per engine, and this results in a four-engine configuration where two engines are mounted under each wing. The size of the engine, approximately 12.8 m long and 2.13 m in diameter, can support the recommended wing configuration and integration requirements. This size approach utilizes matured supersonic propulsion technology and remains flexible regarding thrust margins and operation viability.

Engine placement option was also looked at, previous and current supersonic aircraft. Under-wing mounting, as on the Concorde, has pleasant center-of-gravity characteristics, easy maintenance access, and desirable compression benefit from the wing, but may cause noise and generate possible exhaust flow interaction with the fuselage. Aft-fuselage mounting, applied in airplanes such as Aerion AS2, helps minimize cabin noise and keep the wing aerodynamically clean but shifts weight aft, affecting longitudinal stability and structural requirements. Mounting the engine above the wing or fuselage, as on NASA's X-59, minimizes sonic boom footprint but creates thermal management challenges and design complexity.

Such trade-offs made under-wing mounting the answer for the current configuration. It realizes balancing of aerodynamic performance, center of gravity control, and maintenance by leveraging demonstrated integration expertise with Concorde and other supersonic transports with similar configuration.

3.6 CAD

Within the CAD (Computer-Aided Design) process, the wing geometry, including the external surfaces and control surfaces, is extensively parametrized using knowledge-based engineering rules within a high-fidelity and industry-standard CAD tool. The application of parametric and associative modeling rules enables the possibility for fast geometry and structure architecture updates. The CAD process is used to extract the area distribution along the length of the aircraft (see Fig 9), which is used in the aerodynamic analysis.

3.7 Weight

In this study, the method presented in Part I of John Roskam's Aircraft Design book was used to estimate the maximum takeoff weight, operational empty weight, and fuel weight consumed. In this method, after determining the design data, the specifications of 10 supersonic aircraft provided in the book were extracted. Subsequently, using the relationships provided in Part I of Roskam's Aircraft Design book and determining the required parameters based on the specifications of the Concorde aircraft, the operational empty weight and fuel weight consumed were calculated. The design data and aircraft specifications are presented in table 4.

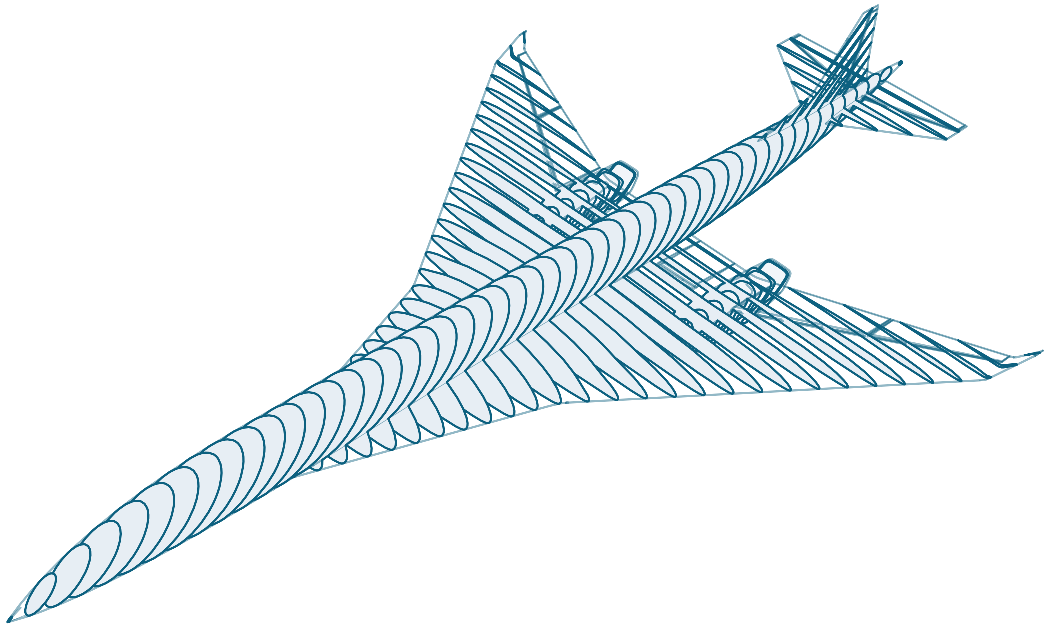

Figure 9: Area Distribution Modeling

Table 4: Specifications of 10 supersonic aircraft presented in the book by Roskam

N	Aircraft	R (NM)	Mach	Pax	Wpl (lbs)	WTO (lbs)	WE(lbs)	WF(lbs)
1	Concorde	3900	2.04	100	20500	389000	172000	202809
2	Tupolev Tu-144	3500	2.15	80	16400	396830	187400	209440
3	Boeing 969_512BB	4000	2.7	183	37515	750000	358270	342824
4	GD_F111A	2660	2.5	2	410	91500	47500	
5	GD_B5 8A	4400	2	3	615	160000	58000	98250
6	NAA B70A	3725	3.08	2	410	550000	190000	300000
7	Rockwell B1B	6478	1.25	4	820	477000		
8	Boeing 969_512BA	-	2.7	-	-	340194	162510	155501
9	SM_SST	-	2.8	-	-	56200	25200	29800
10	NASA Supersonic Cruise	-	1.4	-	-	47900	19620	-

After estimating the maximum takeoff weight and operational empty weight, the weight fractions for each phase were determined based on the data and relationships provided in Roskam's book. Finally, the consumed fuel weight was calculated. The weight fractions are presented in table 5.

Table 5: Weight Fractions of Flight Phases

N	Phase	Fraction
1	Engine start Warm up	0.990
2	Taxi	0.995
3	Take off	0.995
4	Climb1	0.895
5	Subsonic cruise	0.974
6	Climb2	0.895
7	Supersonic cruise	0.701
8	Deceleration, Descend	0.985
9	Subsonic cruise	0.974
10	Descend	0.985
11	Hold	0.927
12	Deceleration, Approach	0.985
13	Land & Taxi	0.992

After estimating the desired weights, the payload-range chart was plotted.

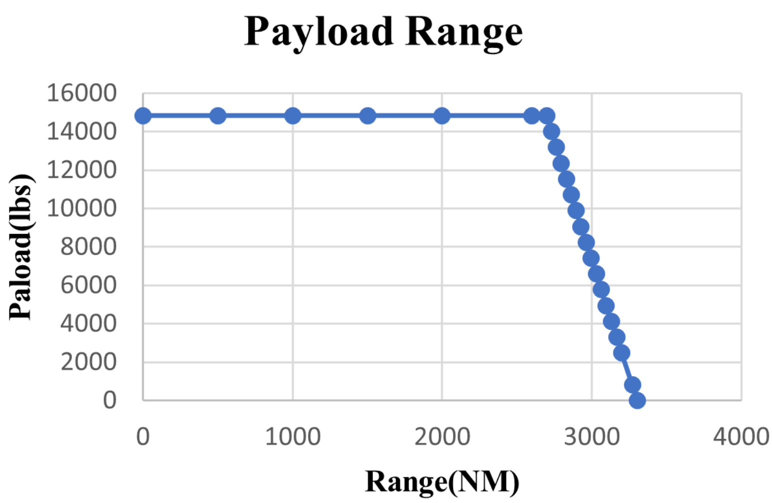

Figure 10: Payload-Range Diagram

3.8 Performance

At the performance module, the required fuel for the accomplishment of the mission is computed. In this process, instead of using simple fuel fraction methods, the equations of motions are solved at each time step the trim condition is determined and the fuel flow is computed accordingly.

3.9 Optimization

A surrogate optimization methodology based on the Design of Experiment (DoE), Neural Network (NN), and Genetic Algorithm (GA) is implemented to find the results. The overall scheme of this framework is presented in Fig 11.

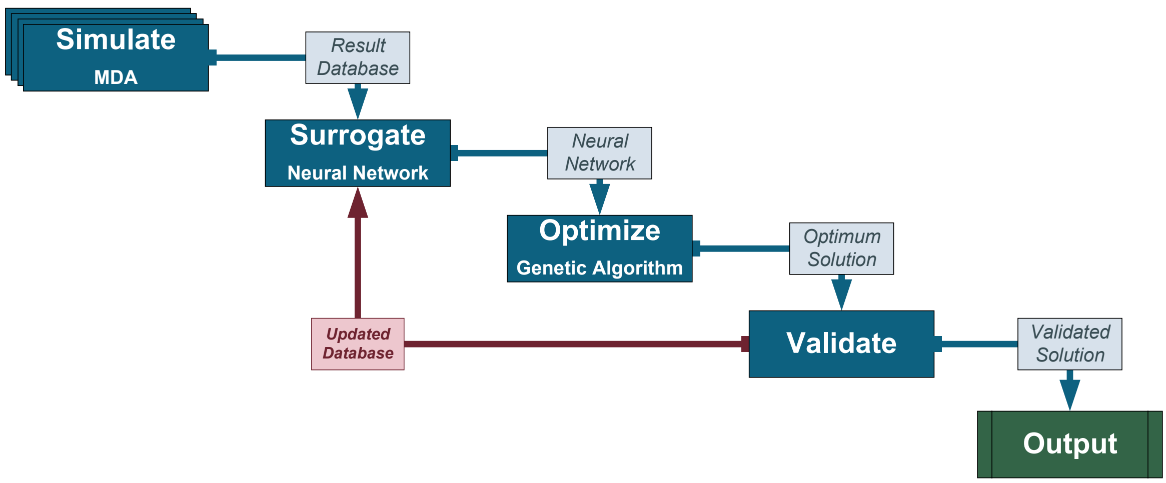

Figure 11: Optimization Process

A population of samples is randomly generated using the Latin Hypercube method, and these samples will be used to populate the database. Each set of design variables is used in the MDA (Multidisciplinary Analysis) process, and the objective functions are calculated. The ANN (Artificial Neural Network) method is implemented to create and train a surrogate model. This surrogate model is used to guess the objective function based on any set of desired design variables. The network has one hidden layer and 50 neurons. A GA (Genetic Algorithm) is then used to find the optimum solution by using the developed surrogate ANN model.

4. Results

A simplified version of the developed method is implemented for the sizing of a 72-passenger Mach 1.6 aircraft. The aircraft is designed for a range of 7,000 km. The aircraft layout is presented in Fig 12.

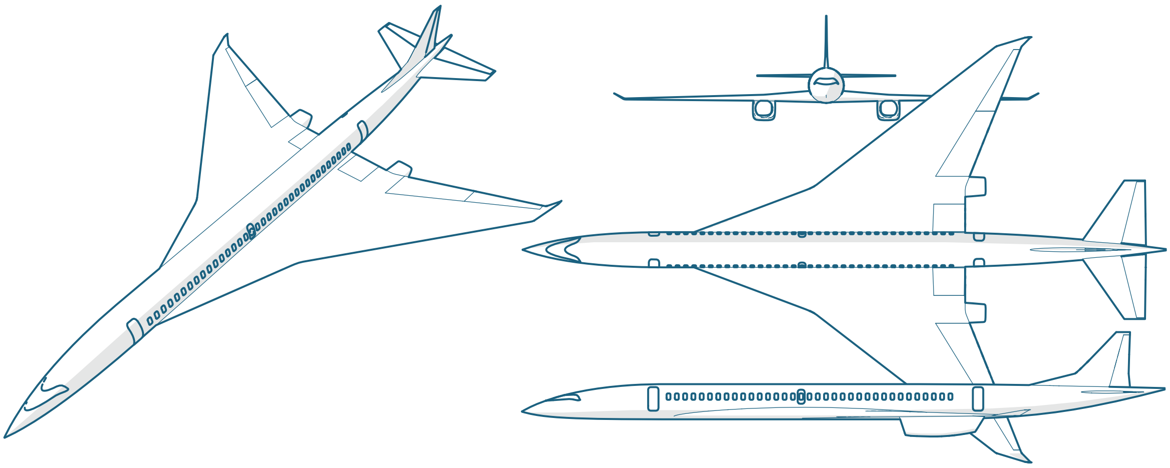

Figure 12: Aircraft Layout

Aircraft key characteristics are presented in Table 6.

Table 6: Aircraft Characteristics

MTOW [*kg*]	131,914.7
Empty Weight [*kg*]	57,828.1
Payload Weight [*kg*]	7,200
Fuel Weight [*kg*]	66,886.5
Wing Area [m^2]	238.0
Engine Thrust [*lbf*]	2x$58,000.0$
Wing Loading (W/S) [lbf/ft^2]	93.2
Thrust Loading (W/W) [lbf/ft^2]	0.4

The aircraft dimensions are tabulated in Table 7.

Table 7: Aircraft Dimensions

	Wing	Horizontal Tail	Vertical Tail
Area [m^2]	238.0	31.8	13.3
Span [*m*]	29.0	9.8	8.0
Aspect Ratio [−]	2.97	3.02	4.8
Sweep LE [*deg*]	52.4	35.0	45.0

5. Conclusion

The scope of an existing civil aircraft multidisciplinary design and optimization framework, namely LAMBDA (Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis), is expanded to cover the design of supersonic transport aircraft. The required aerodynamic and propulsion methodologies are implemented. The developed method is applied for the design of a 72-passenger Mach 1.6 aircraft with a range of $7,000\,[km]$.

The aircraft weight, particularly the structure weight, can be calculated using high-fidelity methods. The computation of sonic boom should be incorporated inside the analysis, to constrain the aircraft performance over lands. Implementation of a more detailed propulsion mode is also envisioned.

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