# APPLICATION OF LAMBDA FRAMEWORK FOR AIRCRAFT MULTIDISCIPLINARY DESIGN, ANALYSIS AND OPTIMIZATION

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## Abstract

For the assessment of new technologies and evaluation of novel aircraft configurations, usually a multidisciplinary approach is required. To this aim, aircraft conceptual design and optimization frameworks, which integrate different disciplines into a single computational environment, are developed. In this research, the applications of the framework LAMBDA (Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis) for the multidisciplinary design, analysis and optimization of civil aircraft are presented. The framework is capable of handling both conventional and novel aircraft configurations. For the propulsion module, the current status provides the possibility of using both turbofan and turboprop engines. The framework provides a high level of customization in terms of the methods used, which is critical for multi-fidelity aircraft optimization. The framework is validated against a regional aircraft, and the framework has estimated the sizing parameters and the aircraft layout with good accuracy. The presented applications are the design of conventional transonic aircraft, optimization of a novel TBW (Truss-Braced Wing) aircraft, and design of a high-speed Mach 1.6 transport aircraft. The implementation has shown that the baseline optimized configuration can be achieved within a very reasonable time, and this baseline configuration can be used for larger-scale design efforts.

**Keywords:** Aircraft Design, Framework, Optimization, MDO (Multidisciplinary Design Optimization)

## 1. Introduction

Air travel is estimated to be increasing by 4% annually, leading to a rise in the number of aircraft. The resulting increment in the produced emissions has raised concerns. As a result, environmental requirements are becoming increasingly stringent to mitigate the environmental impacts of growing aircraft emissions. Given the fact that the TAW (Tube-and-Wing) aircraft configuration has matured over the past decades, meeting the new environmental targets will require the development of novel configurations. Various innovative designs are being explored to achieve these targets, including TBW (Truss-Braced Wing) (see figure 1), BWB (Blended Wing Body), BLI (Boundary Layer Ingestion), HEP (Hybrid Electric Propulsion), TEP (Turboelectric Propulsion), and Hydrogen Propulsion. These new configurations must not only enhance performance and significantly reduce emissions but also be economically and technically feasible.

The conceptual design and optimization of novel aircraft configurations necessitate the integration of multiple disciplines (such as weight, aerodynamics, propulsion, cost, emissions, etc.) into an integrated design process. Given that aircraft design is inherently iterative, utilizing hand calculations or separate design and analysis tools would be both time-consuming and computationally inefficient. This challenge is exacerbated when optimization is involved, as it may require evaluating thousands

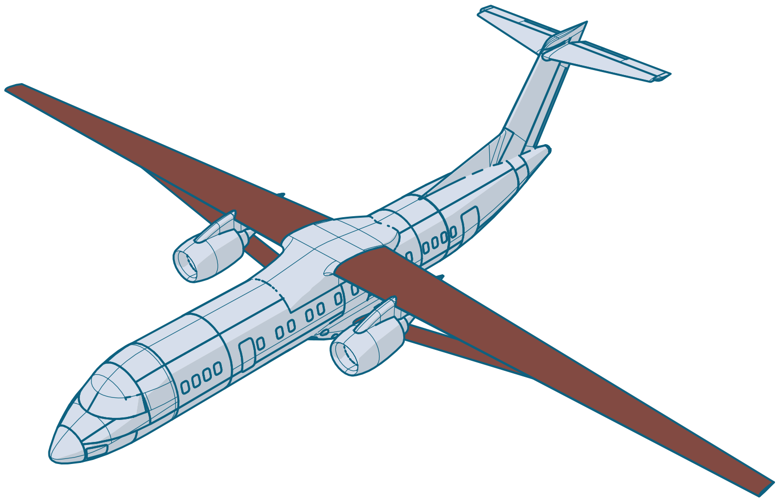


Figure 1 – Proposed TBW Configuration [1]

of design points. Additionally, many design tasks are repetitive and labor-intensive, and automating these processes within a computer program can significantly reduce the workload. To address these challenges, aircraft conceptual design frameworks have been developed and are widely used to optimize novel aircraft and assess new technologies.

In 1976, NASA (National Aeronautics and Space Administration) ARC (Ames Research Center) developed ACSYNT (Aircraft Synthesis) [2], followed by NASA LaRC (Langley Research Center) introducing of FLOPS (Flight Optimization System) in 1984 [3]. The increasing demand for electric and hybrid-electric propulsion systems led NASA LaRC to develop LEAPS (Layered and Extensible Aircraft Performance System) in Python in 2018 to replace FLOPS [4]. The development of program PASS (Program for Aircraft Synthesis Studies) was begun in 1988 by Kroo at Stanford University for aircraft conceptual design with emphasis on the application of AI (Artificial Intelligence). The program Piano [5] for aircraft sizing and emission analysis began as Ph.D. research in 1984 [6]. In 1990, Roskam introduced AAA (Advanced Aircraft Analysis) with a user-friendly interface citeroskam1990. In 1991, Seung-Hyeog at Cranfield University developed an expert system for aircraft design [7]. PrADO (Preliminary Aircraft Design and Optimization Program) software was developed in 1990 at the Technical University of Brunschwig for the conceptual design of hypersonic and subsonic civil aircraft [8]. RDS (Raymer Design Software) software was introduced in 1992 by Raymer as a student analysis tool [9], currently available in both free and professional versions.

In 2002, the QCARD (Quick Conceptual Aircraft Research and Development) was developed for aircraft conceptual design by Isikveren at KTH Royal Institute of Technology using MATLAB language [10]. Based on QCARD, the aircraft design tool CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) was developed in 2008 [11]. The MDOPT (Multidisciplinary Design Optimization) was introduced by LeDoux from Boeing in 2004 [12] for air vehicle optimization and included a GUI (Graphical User Interface) for user input. The software DEE (Design and Engineering Engine) was developed at Delft University of Technology by La Rocca in 2009, with great emphasis on the flexibility of aircraft shape generation and FEM (Finite Element Model) automation [13]. The PreSTo (Preliminary Sizing Tool) tool, which is a set of Microsoft Excel worksheets, was introduced in 2011 by Seeckt from Hamburg University of Applied Sciences [14]. The TASOPT (Transport Aircraft System Optimization) program was developed by Drela at MIT (Massachusetts Institute of Technology), with an emphasis on environmental constraints, and it was used for the design and optimization of BLI aircraft [15].

The VAMPzero [16], developed at DLR (German Aerospace Center), uses CPACS (Common Parametric Aircraft Configuration Schema) [17] for storing and communicating aircraft data. DLR has recently undertaken numerous collaborative aircraft design projects [18, 19, 20, 21, 22]. The AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts) framework, developed by researchers from Europe, Canada, and Russia, facilitates collaborative aircraft design, analysis, and optimization [23]. The geometry-oriented tool RAPID (Robust Aircraft Parametric Interactive Design) [24] was developed at Linköping University in 2013, and later was integrated into the CADLab [25] design framework. In 2015, TUM (Technical University of Munich) developed the ADDAM (Aircraft Design DAta Model) data model in MATLAB for the ADEBO tool [26]. The PyPAD framework, developed in Python at Politecnico di Milano in 2015, focuses on preliminary aircraft design with high-fidelity structure sizing methods [27]. Using Python language, Stanford University introduced SUAVE (Stanford University Aerospace Vehicle Environment) [28] in 2015 and the University of Naples introduced JPAD (Java toolchain of Programs for Aircraft Design) [29] in 2016 for aircraft conceptual design. RADE (Rapid Airframe Design Environment) was developed at Georgia Tech in 2018 to address challenges in high-fidelity structural design during the conceptual phase [30]. In 2019, Cranfield University developed the GENUS aircraft conceptual design environment using Java [31]. DELWARX (Distributed Design Optimization of Large Aspect Ratio Wing Aircraft with Rapid Transonic Flutter Analysis in Linux) framework was developed in Virginia Tech using Python for the Linux operating system, with a focus on distributed computing and transonic flutter analysis [32].

The need for an aircraft design framework existed from the beginning of the conceptual design of the TBW aircraft at AUT (Amirkabir University of Technology, “Tehran Polytechnic”) in 2010. Later in 2015, there was a decision to use an integrated single framework for the design and optimization activities. After review and examination of available tools, it was decided that a new aircraft design framework should be developed. Many reasons contributed to this decision: lack of proper and complete documentation, lack of easy and reliable access, lack of open architecture, reliance on hard-coded single methods for each disciplinary analysis, and reliance on internal methods without links to external tools. Additionally, there was a preference to maintain complete control over the software development process rather than using existing tools. For these reasons, the work on the development of LAMBDA (Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis) started in 2015 with a focus on the design and optimization of the TBW configuration. Currently, the framework has progressed to a stage that performs essential aircraft design and optimization solutions for conventional and novel civil aircraft. LAMBDA is architectured 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.

In the next section, the framework architecture and development process are presented briefly. The framework disciplinary modules are introduced in the next section. The framework validation results against turboprop and turbofan aircraft are presented in the next section. In the last section, the application of the framework for the design of a conventional 92-passenger aircraft, the optimization of a TBW aircraft, and the design of supersonic transport aircraft are presented.

## 2. Framework Development

The LAMBDA framework is used for the design, analysis, and optimization of the investigated aircraft. Details about framework development and framework modules are presented in [33]. A short review of the key features of the framework is presented in the following paragraphs, and interested readers are referred to the mentioned research.

The first step in the framework development was the preparation of the top-level requirements for the framework features and capabilities. These requirements are mainly established based on the lessons learned from the author’s previous experiences in developing stand-alone codes for aircraft design. These requirements are complemented after studying the available tools and investigating their features. Eventually, many requirements were considered for the development of LAMBDA: extensibility, flexibility, multifidelity, usability, modularity, integrability, consistency, accuracy, scalability, diversity, efficiency, applicability, adaptability, and visuality [33].

The framework architecture has been subject to many changes since the beginning of the framework development. The current architecture allows for high levels of modularity and flexibility, which enable the addition of new modules and methods easily. 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.

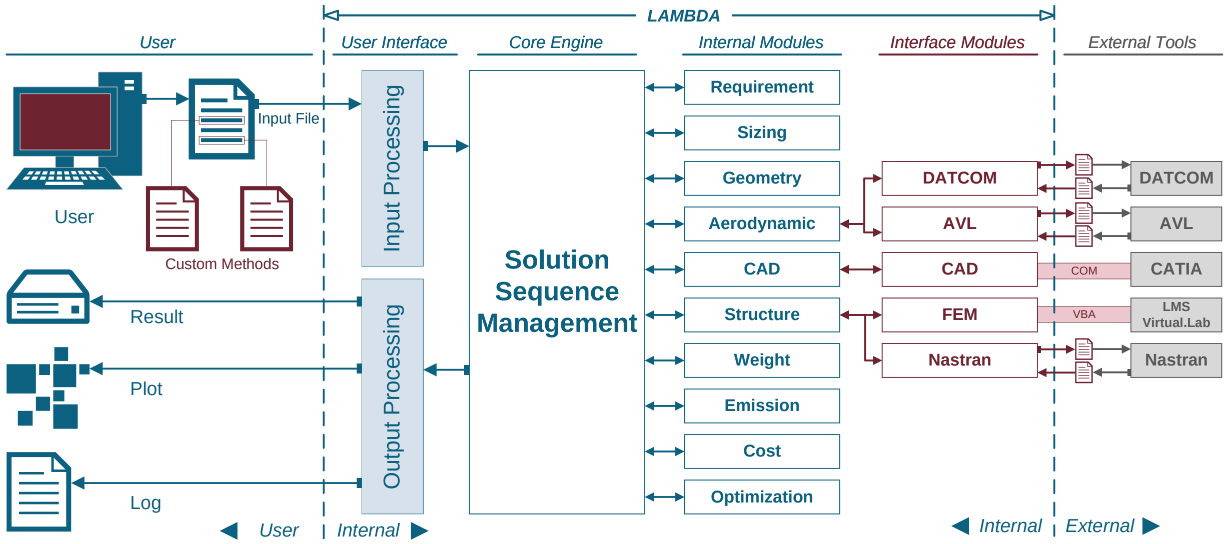



Figure 2 – Framework Architecture [33]

Among available coding languages, MATLAB and Python have been used widely in academia and industry for engineering analysis, and for the development of LAMBDA, it was decided to use MATLAB [34]. Though the GUI approach is sometimes easier to learn and use, it is decided to implement Namelist TUI (Textual User Interface) for the framework. In this approach, all inputs and commands to the software are written in a text file with a specific format that is understandable to the framework. Initially, functional programming was used for the development of the framework, but later, OOP (Object-Oriented Programming) was selected, and previous functions were converted to classes. The LAMBDA features an open architecture, which enables the addition and integration of new methods and modules easily by both developer and user. The user can develop their own scripts and request the framework to use those scripts for the job. The call to these customized scripts is made through the input file, and the framework will use the user scripts instead of built-in functions and methods.

Regarding the integration of external tools, the high-dependency approach is used. In this approach, proven high-fidelity external tools are used, and the data are transferred between the framework and the tool. For example, for the geometry module, the modeling is conducted via a validated external tool, such as CATIA, and only the interface protocol is developed within the framework. Since the current framework is intended to be used for high-fidelity optimizations, and to reduce the development and testing time, the second approach is selected.

## 3. Framework Modules

In the following subsection, a brief introduction to the modules is presented in the following subsections.

**1. Requirement** 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. The requirement module processes the top-level aircraft requirements, which are defined by the user, and develops the requirements' data structure to be used inside the solution. This module parses the input file, detects user commands, and validates the inputs of the command.

**2. Solution** The `Solution` module controls the sequence and order of the execution of different disciplines and the exchange of data among them. As an example, the sequence of execution for `Cost Analysis` is presented in figure 3. Many solutions have a convergence loop that is required for solutions where some of the input data to one or many analysis modules are updated in the downstream modules. For the first iteration, initial values are assigned to the required variables based on the knowledge gathered from similar aircraft.

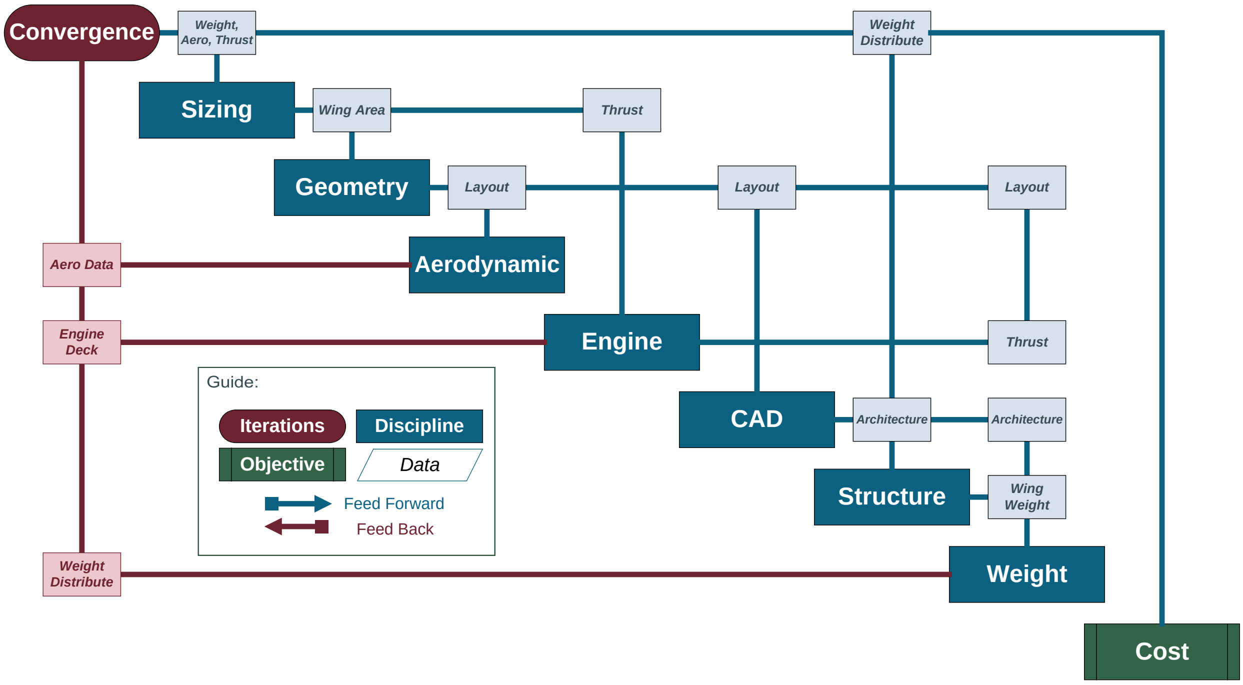



Figure 3 – Typical Solution for Cost Analysis [33]

**3. Sizing** The `Sizing` module calculates the required engine thrust and wing area to fulfill the performance requirements, which are based on the mission and Part-25 requirements. The static sea-level required engine thrust, $T_{sls}$, and the wing area, $S$, are computed using the matching diagram. In subsequent iterations, the classical formulation of the matching diagram available in the textbook [35] is used. The user can select which of these requirements should be considered in the sizing process and can adjust the requirements' values and settings.

**4. Geometry** The `Geometry` module has two core functionalities: Geometry Design, and Geometry Generation. (1) Geometry Design: The geometry design refers to the process of designing a suitable and reasonable planform and defining the key parameters of the wing, fuselage, tail, landing gears, nacelles, and pylons based on the design requirements. The geometry generation process refers to the process where the 3-D geometrical representation of the components is built for the purpose of visualization or simulation pre-processing. The Fuselage layout is designed based on the number of passengers. The wing planform is designed based on cruise Mach number (see appendix A). The horizontal tail and the vertical tail area are dependent on the wing area and are sized using the tail volume coefficient. (2) Geometry Generation: The `Geometry` module, which is implemented in MATLAB, performs simple geometrical operations within the aircraft optimization framework itself and prepares the information for low-fidelity analysis modules. In this approach, the geometrical components are derived from two master classes: Fuselage and Wing. The results of the geometry modules are used by the `CAD` module.

**5. CAD** A dedicated module, namely `CAD` module, is developed in MATLAB which interacts with CATIA [36] through the COM (Component Object Model) interface. The interaction through this interface is done via syntax, which is based on VBA (Visual Basic for Applications) language. This interface can generate CATIA documents, update the geometry in CATIA according to aircraft geometry in MATLAB, and extract geometrical measurements from the CATIA file. The high-fidelity geometry model is usually used for high-fidelity simulations, such as wing weight estimation using FEA (Finite Element Analysis), and aerodynamic analysis using CFD (Computational Fluid Dynamics). In the high-fidelity model, the internal structure architecture is also generated in addition to the external surfaces. Major classes are used to define the aircraft geometrical data: (1) Wing: Each wing consists of many sections, and a segment is defined for each pair of consecutive sections. The wing section parameters are the longitudinal, lateral, and vertical location of a reference point along the chord, chord, incidence, and airfoil (see figure 4); (2) Fuselage: The geometry of the fuselage consists of sections placed longitudinally and segments between each pair of consecutive sections. The parameters that define the fuselage section are the longitudinal, lateral, and vertical location of the center point, width, and height of the section (see figure 5); (3) Tail: The vertical tail, horizontal tail, and canard are defined using the wing class models; and, (4) Cabin: Based on the number of passengers, the cabin layout is defined, which includes the arrangement of the seats, the location of galleys and lavatories, the disposition doors and windows, and the design of the cargo compartment layout.

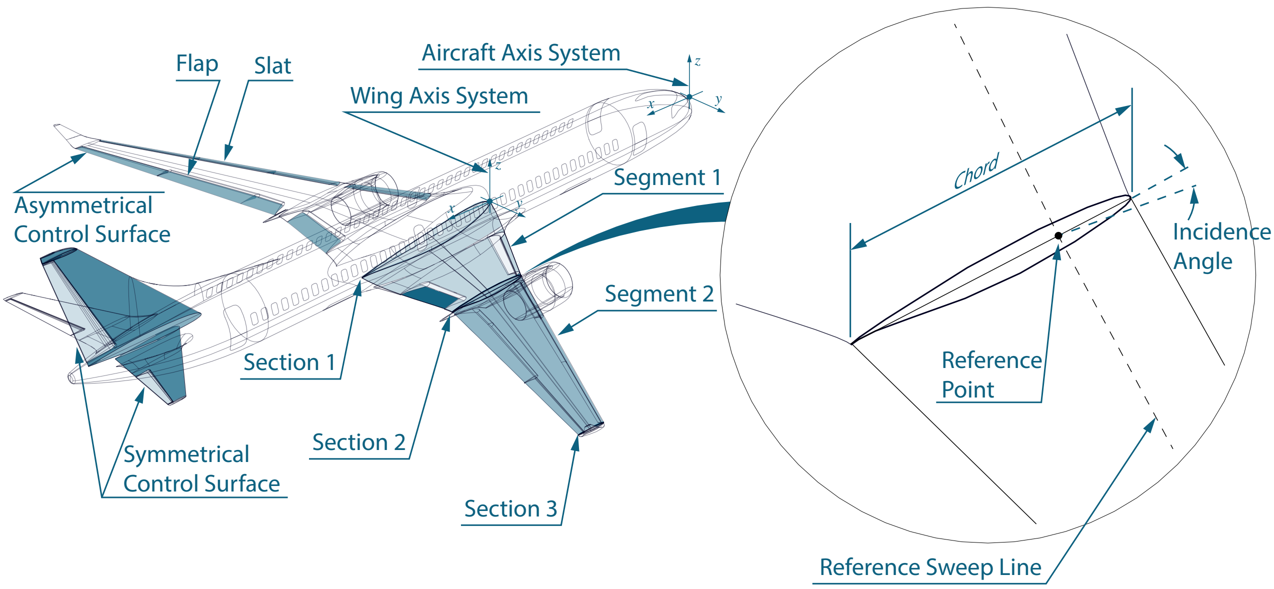



Figure 4 – Wing geometry parametrization.

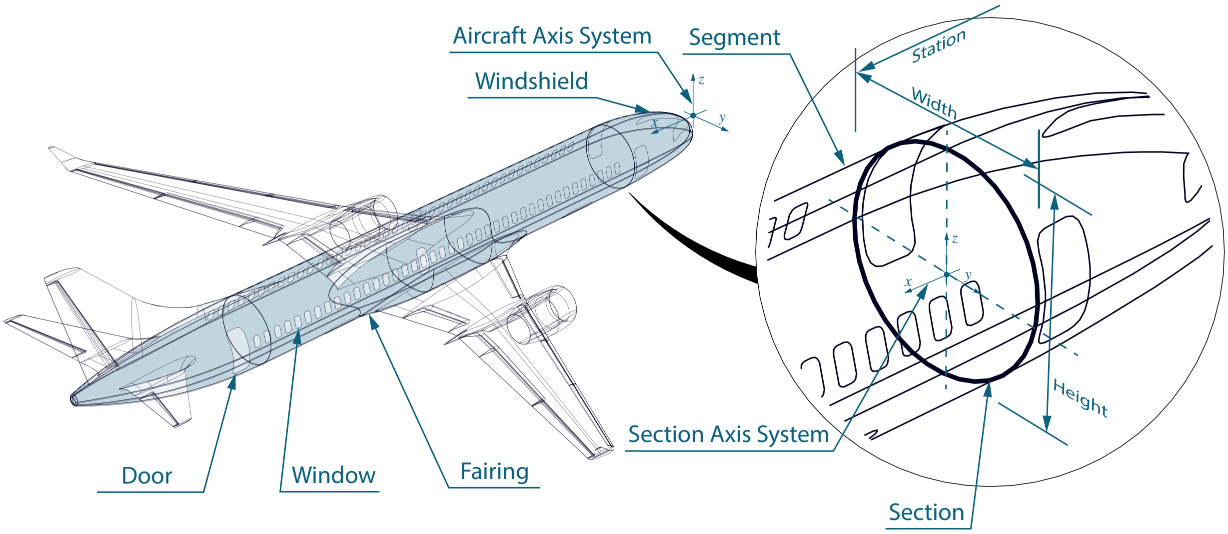
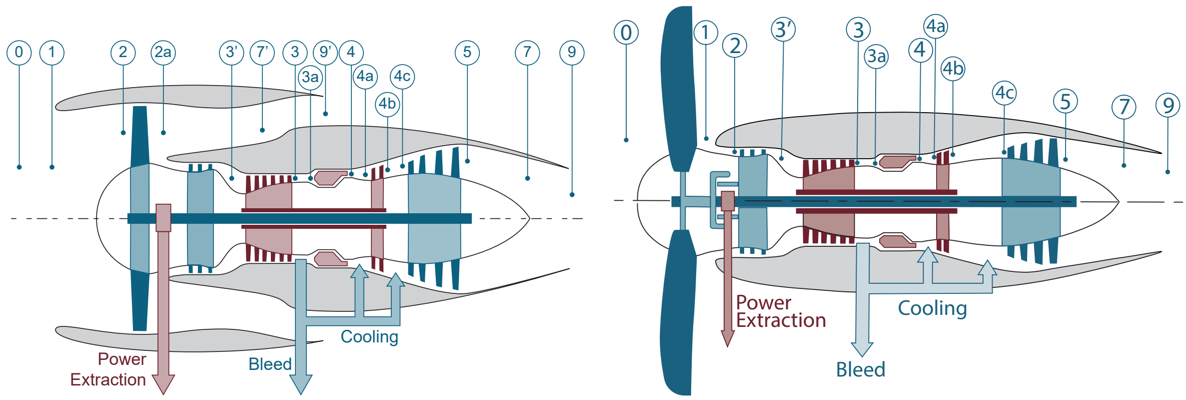



Figure 5 – Fuselage geometry parametrization.

**6. Engine** 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 [37] is incorporated, and the thrust and SFC are scaled from a baseline engine; and, (3) Engine Sizing: The engine performance is computed using the aero-thermodynamic simulations established by Mattingly [38]. The process is implemented in MATLAB to model the performance of different engine layouts [39]. The engine stations for turboprop and turbofan engines are presented in figure 6. The engine cycle is sized to the required thrust and the pre-defined top-level technological requirements of the engine, and the variation of SFC and thrust versus Mach number and altitude are evaluated. The explanation of the engine performance analysis is presented in appendix B.




(a) Turbofan Cycle (b) Turbofan Cycle Front

Figure 6 – Engine Cycles for Engine Sizing and Performance Analysis

**7. Aerodynamic** The `Aerodynamic` module calculates the aerodynamic coefficients, which include lift and drag coefficients at different AOAs (Angle of Attacks) and Mach numbers. Currently, many different methods are available for baseline aerodynamic analysis: (1) Direct Input: Such as the results of external analysis and tests; (2) Engineering Methods: Such as DATCOM code [40] and Textbook method [41]; (3) Low-Fidelity Numerical Methods: Such as AVL (Athena Vortex Lattice) code [42]; and, (4) High-Fidelity Numerical Methods: Works are in progress to add a CFD method as a means to calculate the aerodynamic characteristics.

**8. Structure** The `Structure` module is mainly responsible for the estimation of structural weight using high-fidelity methods. As can be seen from figure 7, this module first employs the `Load` module and FEM module to prepare the initial finite element model. By having this information, and depending on the requested result, the structure is sized according to strength, stiffness, and stability requirements. Nastran [43] is used as the core structure analysis tool. To handle Nastran input and output files, a comprehensive interface module is developed within the framework.

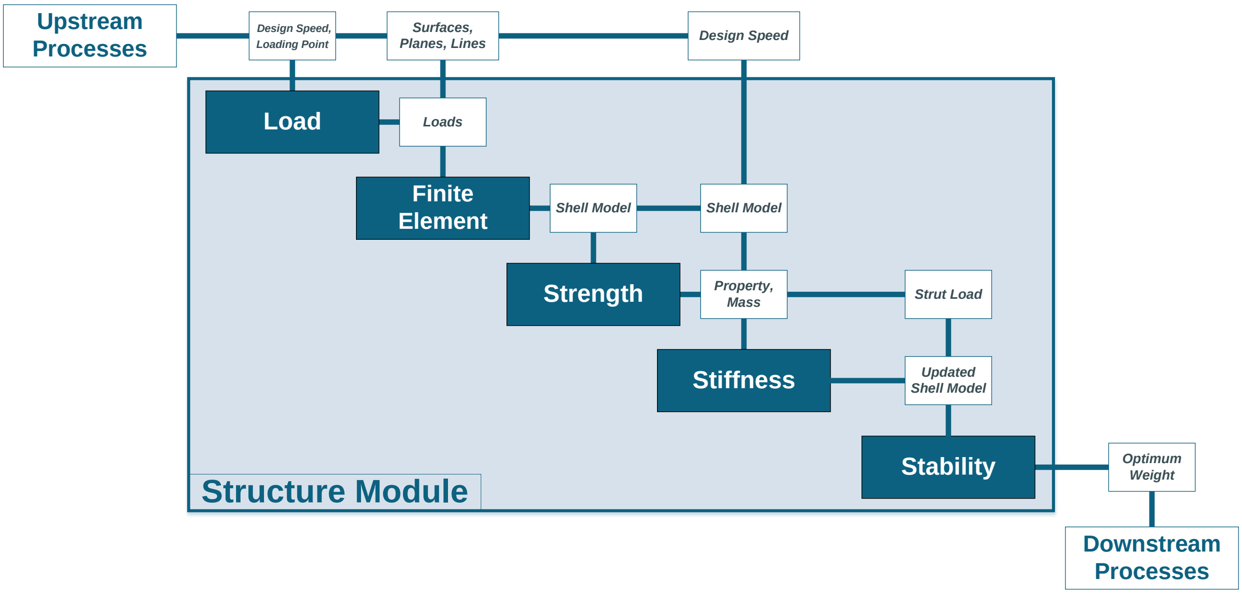



Figure 7 – Structure module process.

**9. Performance** The `Performance` module calculates the performance characteristics of the aircraft. This module includes submodules for: (1) Mission Analysis: The required fuel to complete a custom mission, which is defined by the user, or the achievable range with a fixed amount of fuel is calculated; (2) Payload-Range Diagram: The aircraft mission performance is evaluated at corner points of the payload-range diagram, and the payload-range plot is generated; and, (3) Flight Envelope: The aircraft performance limitations in terms of altitude and speed are calculated, and the flight envelope ($V-H$) is plotted.

**10. Weight** The `Weight` module has many functionalities, which can be requested by the user: (1) Weight Breakdown: The purpose of the weight breakdown analysis is to calculate the buildup of the MTOW (Maximum Take-Off Weight).; (2) Weight Limitation: This function calculates the CG (Center of Gravity) limitations, which can be used later for other processes, such as tail sizing; and, (3) Weight Distribution: If the wing load analysis is requested to perform wing weight sizing using FEA, the weight distribution across the span for the wing is required.

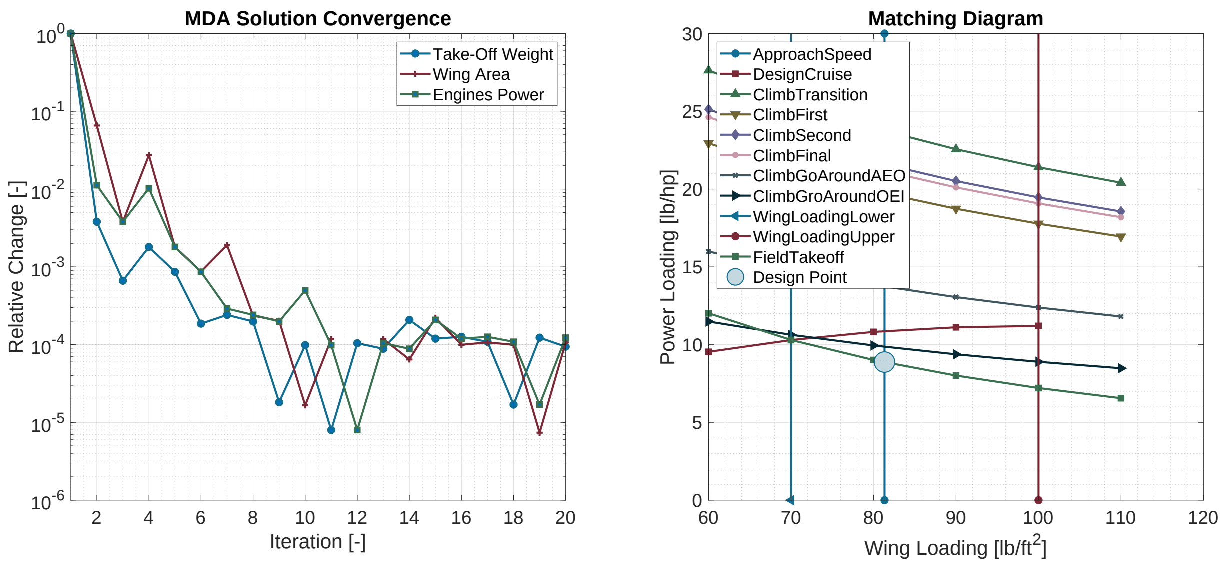
**11. Emission** The `Emission` module calculates the emissions of aircraft in terms of emission mass and temperature response, and these parameters can be used in the optimization process as objective functions. The accounted species are Carbon Dioxide ($CO_2$), Water vapor ($H_2O$), Sulfate ($SO_4$), Nitrogen Oxides ($NO_x$), Methane ($CH_4$), long-lived Ozone ($O_{3L}$), short-lived Ozone ($O_{3S}$), Soot, and contrails. The details of the implemented formulations to calculate the emission index and temperature response are presented by the authors in a previous publication [44].

**12. Cost** The `Cost` module is performed to calculate the operating and life cycle costs. These costs can be used as objectives in the optimization problem. The aircraft cost analysis is mainly based on the method presented by Roskam [45], and minor modifications are implemented. The cost module is capable of distributing the cost over years of operation and production, which would make it possible to find the break-even point.

**13. Optimization** The SBO (Surrogate Based Optimization) [46], which is sometimes called the Metamodel-Assisted Optimization [47], is implemented in the `Optimization` module. In this approach, the costly objective function is replaced with a cheap representation of the original model, which is called the surrogate model. This surrogate model can be optimized much faster than the original model to provide optimum candidates The process employs DoE (Design of Experiment) for creating the sample points, ANN (Artificial Neural Network) for training surrogate models, and GA (Genetic Algorithm) for finding the optimum candidates. The implemented approach provides the capability of optimizing the aircraft with respect to different single objectives or multiple objectives using a single batch of simulations. In section C, the implemented algorithm is presented in algorithm 1.

## 4. Framework Validation

The developed framework is employed for the design of a regional twin-turboprop aircraft, namely the Antonov An-140-100. The aircraft has a capacity of 52 passengers, a range of $2{,}330$ $[\mathrm{km}]$ (with reserves), and a MTOW of $21.5$ $[\mathrm{t}]$ [48]. The cruise long-range speed is $440$ $[\mathrm{km/h}]$ at an altitude of $20$ $[\mathrm{kft}]$, and a reserve of $45$ $[\mathrm{min}]$ is assumed. The aircraft wing area and engines' power are sized for an approach speed of $215$ $[\mathrm{km/h}]$, take-off field length of $4{,}600$ $[\mathrm{ft}]$, and climb gradients. The wing has a trapezoidal planform, equipped with double-slotted flaps, without slats. The 52 passengers are arranged in single-class with a seat pitch of $78$ $[\mathrm{cm}]$ $(30.7$ $[\mathrm{in}])$. For the design purpose, the horizontal tail and vertical tail volume coefficients are $1.2$ and $0.09$, respectively. The solution is converged after 20 iterations (see figure 8a). The matching diagram is presented in figure 8b.




(a) Design Convergence

(b) Matching Diagram

Figure 8 – Convergence and Matching Diagram of the Turboprop Validation

The key parameters of the designed aircraft are compared with the reference aircraft values in table 1. As can be seen, the key parameters of the designed aircraft are close to the reference aircraft. Exceptions are the tail area, which is sized using tail volume coefficients. More detailed methods, which consider the aircraft stability and controllability requirements are being considered for implementation in the framework.

Table 1 – Comparison of Key Parameters of Turboprop Validation

| Parameter | Unit | An-140-100 [48] | Validation | Error |
|---|---|---|---|---|
| MTOW | kg | 21,500 | 21,534 | 0.16 [%] |
| OEW | kg | 13,200 | 13,071 | −0.98 [%] |
| Wing Area | $m^2$ | 56.36 | 54.23 | −3.78 [%] |
| Wing Span | m | 25.5 | 25.36 | −0.52 [%] |
| Fuselage Length | m | 21.57 | 22.23 | 3.07 [%] |
| Fuselage Diameter | m | 2.80 | 2.81 | 0.29 [%] |
| Horizontal Tail Area | $m^2$ | 17.35 | 15.85 | −8.64 [%] |
| Vertical Tail Area | $m^2$ | 12.30 | 13.52 | 9.94 [%] |

The comparison of the designed aircraft layout with the reference aircraft is presented in figure 9.

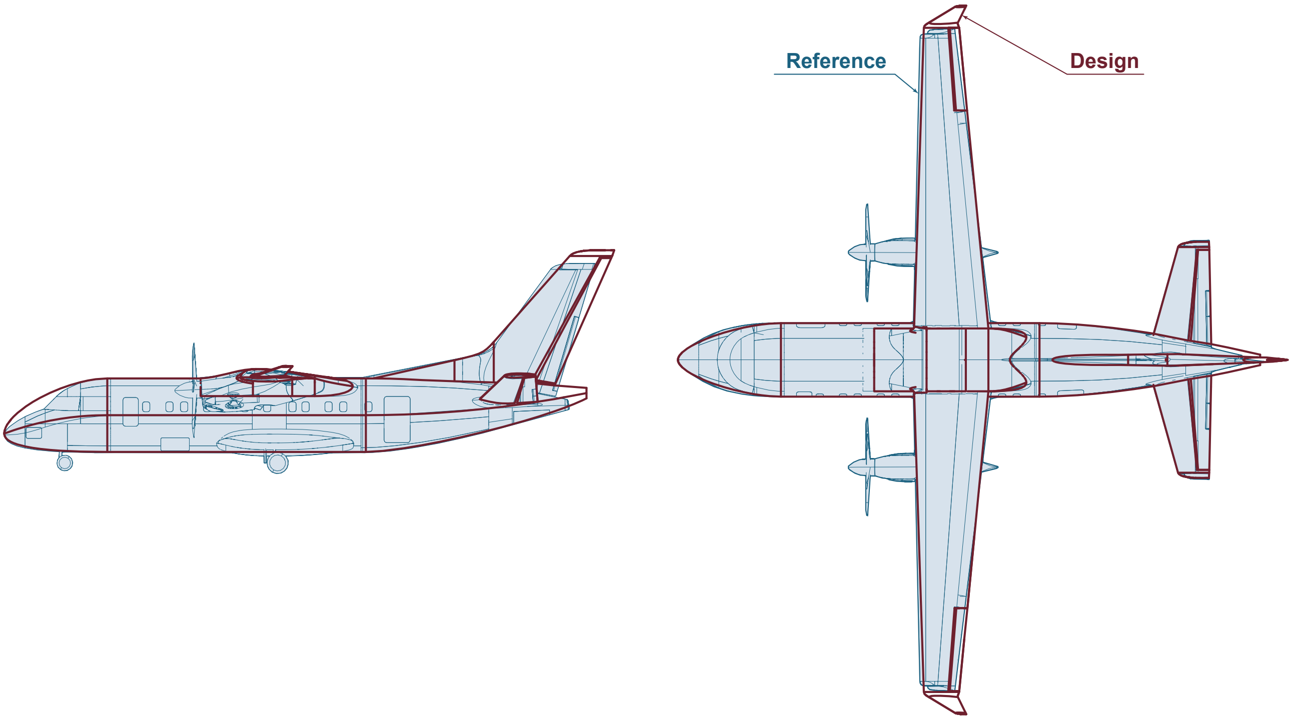



Figure 9 – Comparison of Designed Aircraft and Reference Aircraft

## 5. Framework Application

The developed framework is applied to many civil aircraft design, analysis, and optimization problems. In this section, a few examples of these applications and key results are presented. These applications are:

1. Design of a Conventional Aircraft;
2. Design of a Novel TBW Aircraft;
3. Optimization of the TBW Aircraft; and,
4. Design of a Supersonic Transport Aircraft.

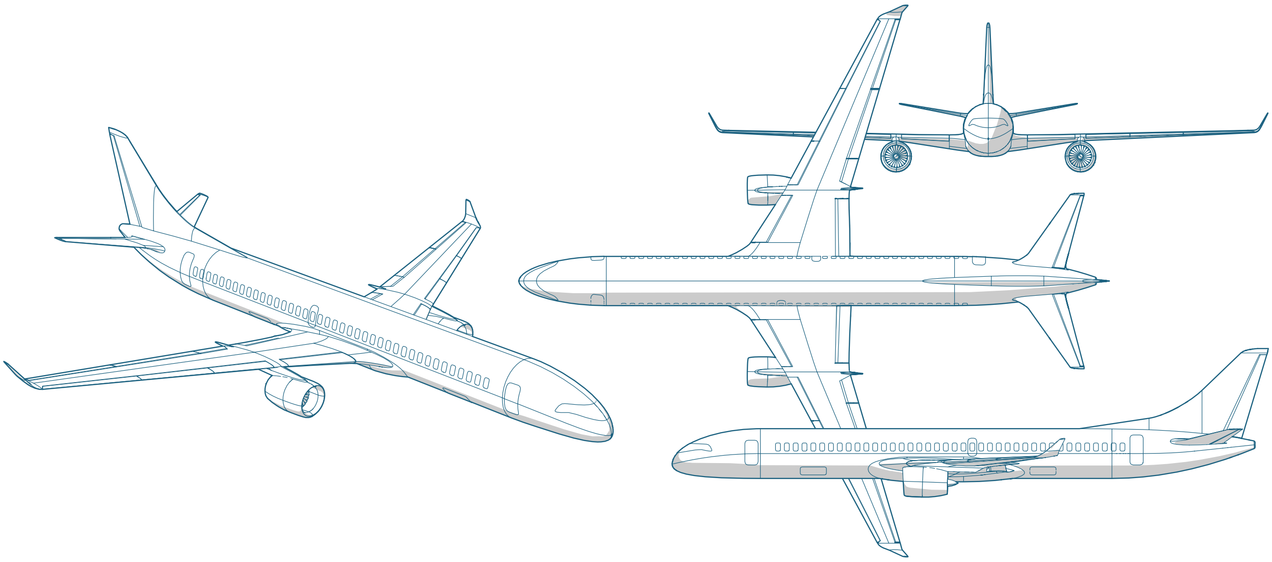


Figure 10 – Aircraft layout of a new conventional regional aircraft.

In the current version of the framework, novel propulsion architectures and AAM (Advanced Air Mobility) configurations are not supported yet, as the implementation of such systems affects the cores of the performance module.

## 5.1 Design of a New Conventional Aircraft

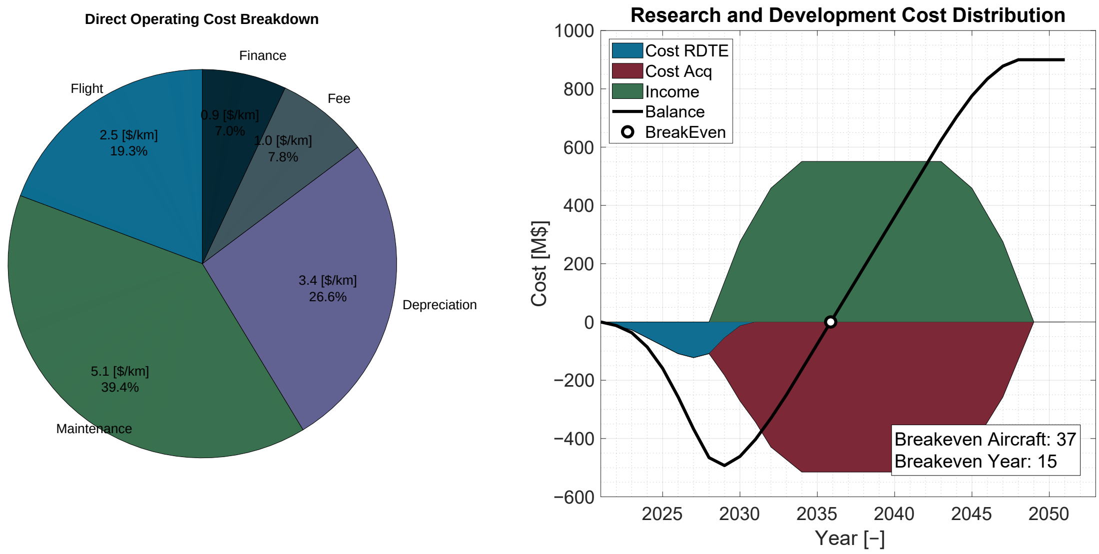
The primary goal of this problem is to design a 92-passenger regional aircraft and calculate the operation costs. The aircraft is a twin-engine aircraft with under-the-wing mounted engines, low wings, 4-abreast fuselage, and conventional tails. The aircraft layout is presented in figure 10.

For cost analysis, the aircraft mission performance is calculated, for which engine performance and aerodynamic analysis are required. The aircraft weight is calculated depending on the geometry, and engineering methods are used. The aircraft development cost is calculated, which takes into account the aircraft weight and standard assumptions from [45]. The results of the cost analysis are presented in figure 11.

## 5.2 Design of a Novel Regional Aircraft

In this application, a trapezoidal very high aspect ratio wing is used to increase the aerodynamic performance, and a truss is added to mitigate the wing weight increment. Conventional fuselage, nacelle, pylons, landing gears, and tail incorporated. The resulting configuration, which is named “TBW-06”, is presented in figure 12a and the results are compared to a CLW (Cantilever Wing) configuration with a similar mission. By applying these changes, the aircraft MTOW is 24,883 kg, and the fuel weight is reduced from 5144 kg in the CLW to 4558 kg in the TBW. Additionally, the DOC has reduced from $235.4\,\$/pax/trip$ in the CLW to $224.1\,\$/pax/trip$ in the TBW.

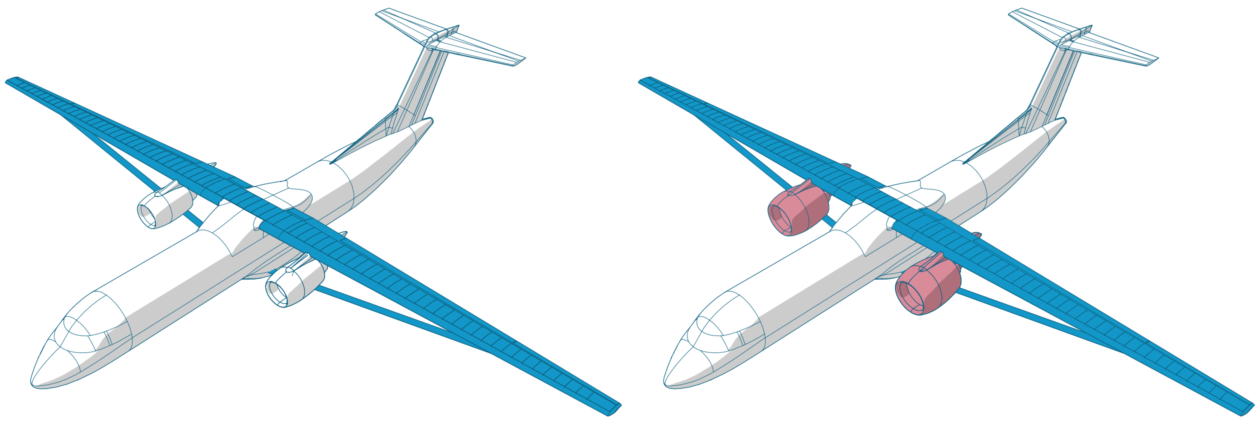
In the next iteration of the design, the HBPR (High Bypass Ratio) engines are replaced with VHBPR (Very High Bypass Ratio) ones to achieve more reduction in fuel consumption. The resulting configuration is named “TBW-12” and is presented in figure 12b. Geometrically, the engine replacement will entail a growth in engine diameter, which increases the drag and decreases the lift over the pylon region. The application of VHBPR engines also has consequences on the weight of the nacelle, pylon, and the engine itself. The fuel weight is reduced by 1296 kg (25.2%) in this aircraft relative to the CLW version, which is the result of both increased aerodynamic performance due to a higher aspect ratio and lowered fuel consumption due to a higher bypass ratio. Also, this configuration has a lower wing weight (2128 kg) compared to the CLW configurations (2436 kg) as the result of two




(a) DOC (Direct Operating Cost) breakdown (b) Cost distribution over years

Figure 11 – Results of cost module for new 92-passenger conventional aircraft.

factors, mainly due to the strut and secondly from reduced take-off weight.



(a) Affordable TBW with HBPR engines (TBW-06) (b) Affordable TBW with VHBPR engines (TBW-12)

Figure 12 – Application of the Framework for Design of a Novel Regional Aircraft

## 5.3 Optimization of Novel Regional Jet

The developed framework is employed for the optimization of the regional TBW aircraft to minimize multiple objectives. The optimization objectives are cost in terms of DOC and weight in terms of MTOW. The optimum aircraft layouts are plotted in figure 13.

The framework is capable of performing a 2-D sensitivity analysis (see figure 14a), in which the variation of each objective to changes in each pair of design variables is investigated, while other design variables are constant. In figure 14b, the variation of cruise aerodynamic performance and wing weight is investigated. In this figure, the randomly generated DoE samples are in blue, the affordable design cases are in simple red (TBW-06, TBW-12, CLW-06, and CLW-12), and the weight-optimum and cost-optimum design points are in bold red. As can be seen, the take-off weight and cruise $L/D$ ratio drive the optimum design in contradicting directions. Generally, as the wing span increases, the $L/D$ increases, but not uniformly due to different nacelle and strut drag.

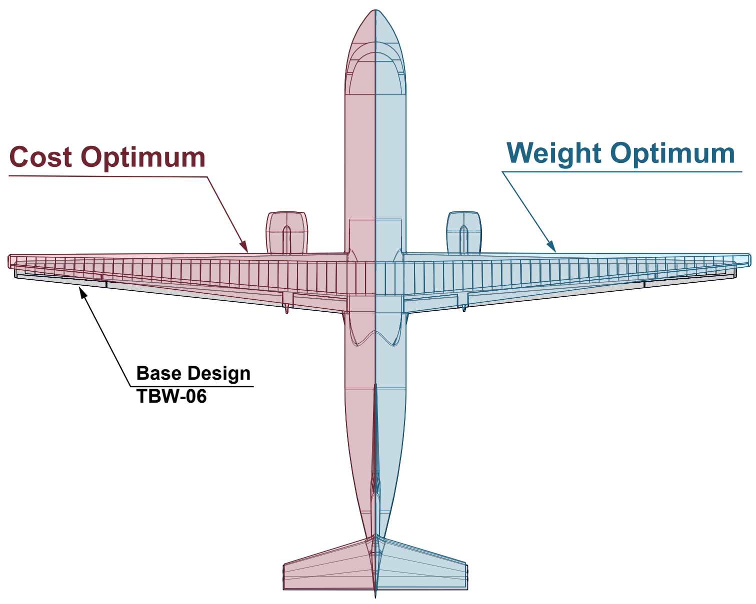
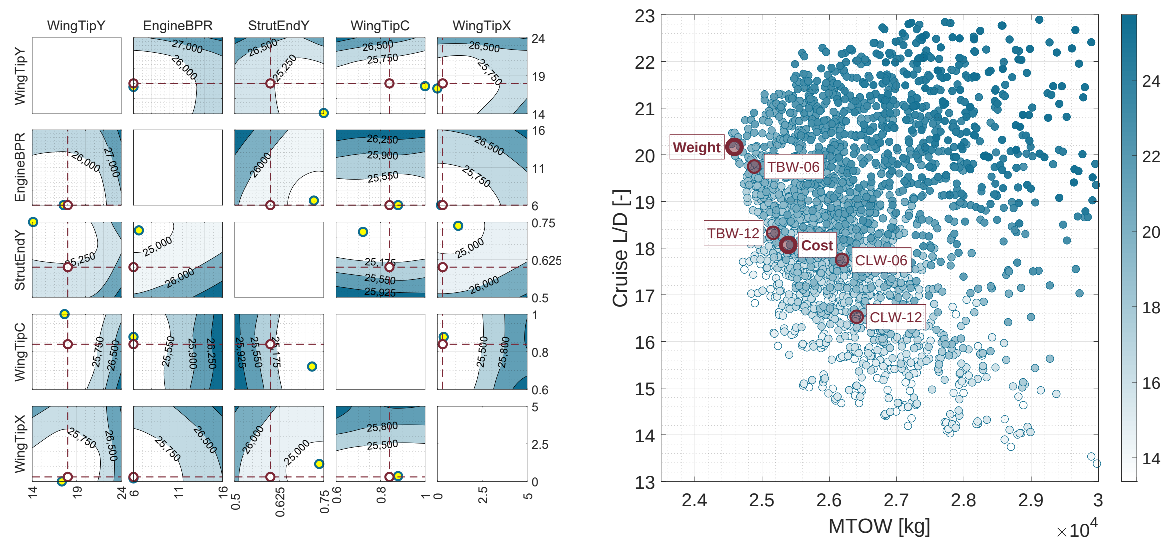



Figure 13 – Aircraft Optimum Layout




(a) Sensitivity Analysis

(b) Pareto Front

Figure 14 – Results of the Optimization of a Novel Regional Aircraft

## 5.4 Design of High-Speed Transport Aircraft

The framework is employed for the design of a Mach 1.6, 7000 km range, 72-passenger aircraft. This base layout is then geometrically designed in the developed framework using a highly parameterized high-fidelity modeling tool. The shape of the cross-section is assumed to be a complete circle, which will have less structural weight and an easier manufacturing process. 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. A comfort seat pitch is selected, which is used to determine the seating zone length. The lengths of the nose and tail sections of the fuselage are computed using assumed fineness ratios of 4.0 and 7.0, respectively. The nose section has a drop angle of $3^\circ$ to improve pilot visibility, and the tail section has an upsweep angle of $4^\circ$ to allow rotation clearance during take-off. A "Cranked Arrow" wing planform is selected and is parametrized at three sections: root, kink, and tip. The airfoils are NACA series 6 with a thickness ratio of 4%

at the root and kink and 3% at the tip. Based on the data provided by Roskam for supersonic aircraft [49], 0.5 and 0.06 are selected for the volume coefficient of the horizontal tail and vertical tail, respectively. Symmetrical NACA series 6 airfoil with a thickness ratio of 3% is used for both horizontal and vertical tails. The aerodynamic lift and drag characteristics are required for sizing and performance analysis. The subsonic aerodynamic characteristics are computed using the build-up method [50]. The supersonic wave drag is computed using the supersonic area rule. The CAD (Computer-Aided Design) process is used to extract the area distribution along the length of the aircraft (see Figure 15), which is used in the aerodynamic analysis. The aircraft layout is presented in Figure 16. Aircraft key characteristics are presented in Table 2.

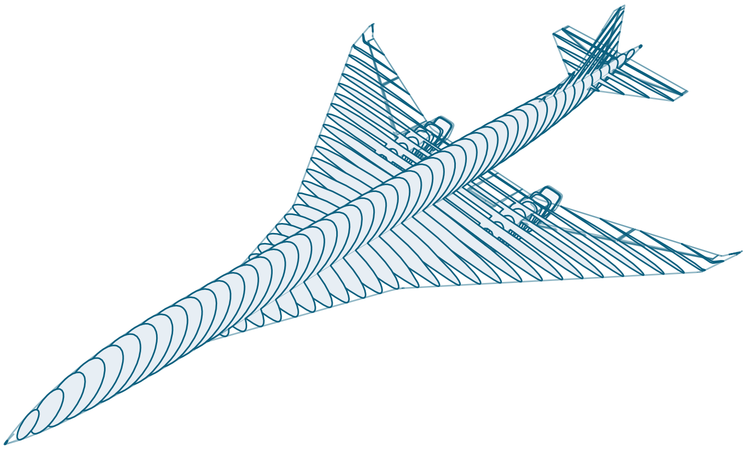


Figure 15 – Area Distribution Modeling

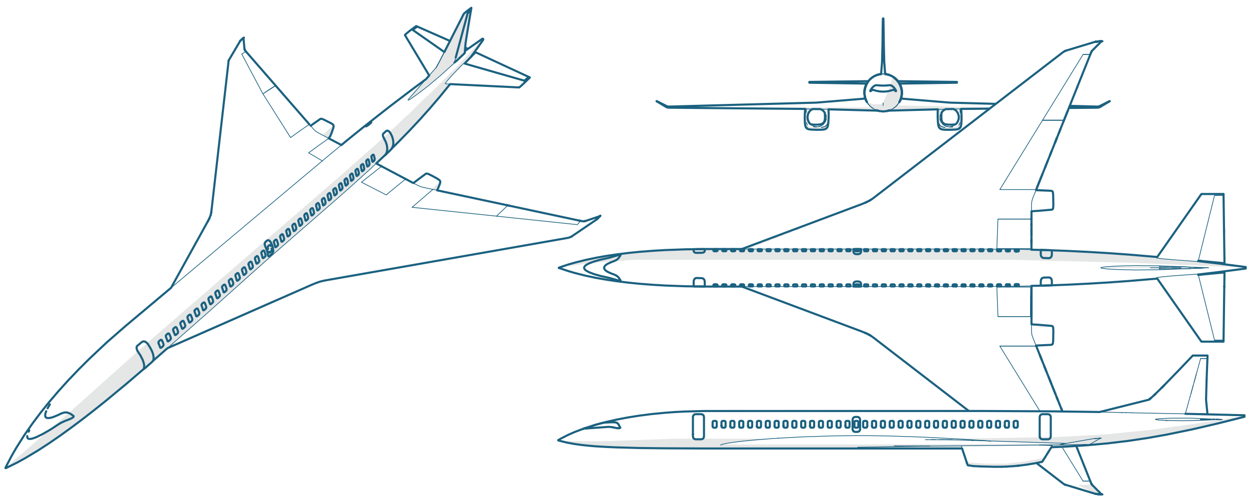


Figure 16 – Supersonic Transport Aircraft Layout

Table 2 – Supersonic Transport Aircraft Characteristics

| Parameter | Value |
|---|---|
| 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 $[lbf]$ | $2x58,000.0$ |
| Wing Loading (W/S) $[lbf/ft^2]$ | 93.2 |
| Thrust Loading (W/W) $[lbf/ft^2]$ | 0.4 |

## 6. Conclusions

The applications of framework LAMBDA (Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis) for aircraft design, analysis, and optimization are introduced. This framework, which is developed using MATLAB in AUT (Amirkabir University of Technology, "Tehran Polytechnic"), has an open architecture that enables the extension of the built-in analysis tools from low-fidelity to high-fidelity. The developed framework can be employed for different types of aircraft design problems, such as design from scratch, design of variants, design of novel configurations, and Technology assessment. The presented results of the validation show very good accuracy in the estimation of key parameters and design of aircraft layout. The framework is used for the design of conventional transonic aircraft, optimization of a novel TBW (Truss-Braced Wing) aircraft, and design of a high-speed Mach 1.6 transport aircraft.

The flexibility of the framework and the quality of the results have encouraged the authors to further develop the framework to include novel propulsion architecture and high-fidelity aerodynamic methods into the framework. The work is in progress to increase the computational speed, particularly in the structure analysis module, in which the third-party 3-D structure meshing tool will be replaced with a MATLAB or Python meshing code. On the aerodynamic side, the high-fidelity aerodynamic analysis using CFD (Computational Fluid Dynamics) is being implemented and integrated into the framework, which can enable analysis of the aerodynamic characteristics using high-fidelity tools, and performing aerodynamic shape optimization and wing high-fidelity aero-structure optimization. In the current implementation, the developed framework can handle only gas-powered turbofan and turboprop engines, and the work is planned for the integration of novel propulsion technologies, such as hybrid-electric, turboelectric, and hydrogen-powered propulsions.

## Appendix A Wing

The design of the wing planform can be linked to the cruise Mach number. The developed method, which applies to both kinked and trapezoidal wings, is derived from the method presented in [51], which itself was based on the data provided in [50, 52]. In the implemented approach, the wing area, wing span, and kink spanwise location are input values (design variables), and the chord of sections and sweep angle of segments are computed. The wing parameters for the kinked wing are depicted in figure 17.

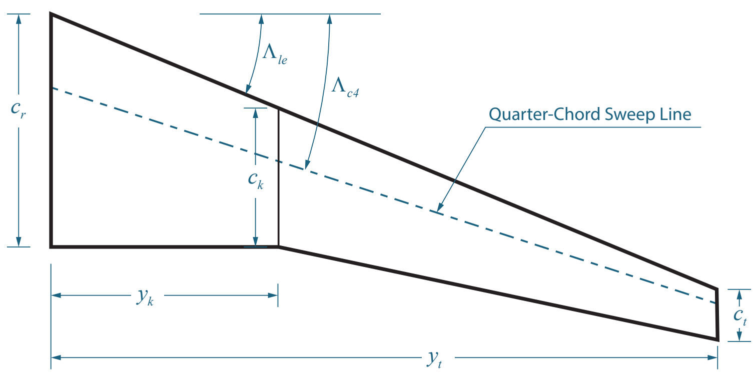



Figure 17 – Kined wing parameters.

The wing quarter-chord sweep angle ($\Lambda_{c4}$) is computed from:

$$\Lambda_{c4} = \begin{cases} 0 & M_{cr} < 0.66 \\ \arccos\left(\dfrac{1.16}{M_{cr}+0.5}\right) & M_{cr} \geqslant 0.66 \end{cases} \tag{1}$$

in which $M_{cr}$ is the cruise Mach number. The taper ratio ($\lambda$) is computed from:

$$\lambda = -0.0083\Lambda_{c4} + 0.4597 \tag{2}$$

where $\Lambda_{c4}$ is in degrees. Using these parameters and geometrical operations, which the details are presented in [33], the wing planform can be developed.

## Appendix B Engine

Aero-thermodynamic simulation, a straightforward yet effective approach, is employed for the analysis of engine performance [38]. This technique ensures the conservation of mass, momentum, and energy across each component. The thermodynamic aspect of the simulation is characterized by the ratio of total and static pressures (denoted as $\pi$) and the temperature ratio (denoted as $\tau$) of each component. The aerodynamic aspect, on the other hand, takes into account the equations for losses in the intake and the Mach number at the engine exit nozzle.

In this paper, the engine is sized to the required thrust or power by determining the primary design choices of the engine, including TIT (Turbine Inlet Temperature), Stagnation Temperatures Ratio of Low to High-Pressure Turbine ($\tau_t$), and OPR (Overall Pressure Ratio). The engine mass flow rate ($\dot{m}_0$) is then computed to achieve the desired thrust or power.

The outcomes of the engine sizing process are then utilized in off-design analysis. This analysis evaluates the variations in SFC (Specific Fuel Consumption) and thrust or power as a function of both Mach number and altitude. As a summary, the main inputs and outputs of the simulation are mentioned in table 3.

Table 3 – Engine Analysis Inputs and Outputs

| Parameter | Description | On-Design | Off-Design |
|---|---|---|---|
| $M_0$ $[kg]$ | Flight Mach Number | Input | Input |
| $h$ $[kg]$ | Flight Altitude | Input | Input |
| TIT | Turbine Inlet Temperature | Input | Output |
| OPR | Overall Pressure Ratio | Input | Output |
| $\tau_t$ | Stagnation Temperatures Ratio | Input | Output |
| $T$ or $P$ | Thrust or Power | Input | Output |
| $\dot{m}_0$ | Engine Mass Flow Rate | Output | Output |
| SFC | Specific Fuel Consumption | Output | Output |
| $\eta$ | Overall Efficiency | Output | Output |

## Appendix C Optimization

The implemented SBO (Surrogate Based Optimization) algorithm is presented in algorithm 1.

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## 8. Copyright Statement

**Algorithm 1:** Implemented Metamodel-Assisted Optimization

**Data:** Initial sample size $N$, maximum number of iterations $maxIter$, convergence tolerance $\varepsilon$
**Result:** Optimal design $\mathbf{x}^*$

Generate $N$ initial sample points $\mathbf{x}$ using DoE (Design of Experiment);
Simulate sample points $\mathbf{x}$ to evaluate objective functions;
**for** *each objective* **do**
  **while** *not converged and iteration* $< maxIter$ **do**
    Train surrogate model $f(\mathbf{x})$ using ANN (Artificial Neural Network);
    Find candidate solution $\mathbf{x}_{\text{cand}}$ using GA (Genetic Algorithm) applied to surrogate model $f(\mathbf{x})$;
    Simulate candidate solution $\mathbf{x}_{\text{cand}}$ to evaluate objective function;
    **if** *convergence criteria met* **then**
      Optimal design $\mathbf{x}^*$ is $\mathbf{x}_{\text{cand}}$;
      Terminate optimization;
    **else**
      Update sample points $\mathbf{x}$ with $\mathbf{x}_{\text{cand}}$;
    **end**
  **end**
**end**



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## Abbreviations

**AAA** Advanced Aircraft Analysis
**AAM** Advanced Air Mobility
**ACSYNT** Aircraft Synthesis
**ADDAM** Aircraft Design DAta Model
**AGILE** Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
**AI** Artificial Intelligence
**ANN** Artificial Neural Network
**AOA** Angle of Attack
**ARC** Ames Research Center
**AUT** Amirkabir University of Technology, "Tehran Polytechnic"
**AVL** Athena Vortex Lattice
**BLI** Boundary Layer Ingestion
**BWB** Blended Wing Body
**CAD** Computer-Aided Design
**CEASIOM** Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods
**CFD** Computational Fluid Dynamics
**CG** Center of Gravity
**CLW** Cantilever Wing
**COM** Component Object Model
**CPACS** Common Parametric Aircraft Configuration Schema
**DEE** Design and Engineering Engine
**DELWARX** Distributed Design Optimization of Large Aspect Ratio Wing Aircraft with Rapid Transonic Flutter Analysis in Linux
**DLR** German Aerospace Center
**DOC** Direct Operating Cost
**DoE** Design of Experiment
**FEA** Finite Element Analysis
**FEM** Finite Element Model
**FLOPS** Flight Optimization System
**GA** Genetic Algorithm
**GUI** Graphical User Interface
**HBPR** High Bypass Ratio
**HEP** Hybrid Electric Propulsion
**JPAD** Java toolchain of Programs for Aircraft Design
**LAMBDA** Laboratory of Aircraft Multidisciplinary Knowledge-Based Design and Analysis
**LaRC** Langley Research Center
**LEAPS** Layered and Extensible Aircraft Performance System
**MDO** Multidisciplinary Design Optimization
**MDOPT** Multidisciplinary Design Optimization
**MIT** Massachusetts Institute of Technology
**MTOW** Maximum Take-Off Weight
**NASA** National Aeronautics and Space Administration
**OEW** Operating Empty Weight
**OOP** Object-Oriented Programming
**OPR** Overall Pressure Ratio
**PASS** Program for Aircraft Synthesis Studies
**PrADO** Preliminary Aircraft Design and Optimization Program
**PreSTo** Preliminary Sizing Tool
**QCARD** Quick Conceptual Aircraft Research and Development
**RADE** Rapid Airframe Design Environment
**RAPID** Robust Aircraft Parametric Interactive Design
**RDS** Raymer Design Software
**SBO** Surrogate Based Optimization
**SFC** Specific Fuel Consumption
**SUAVE** Stanford University Aerospace Vehicle Environment
**TASOPT** Transport Aircraft System Optimization
**TAW** Tube-and-Wing
**TBW** Truss-Braced Wing
**TEP** Turboelectric Propulsion
**TIT** Turbine Inlet Temperature
**TUI** Textual User Interface
**TUM** Technical University of Munich
**VBA** Visual Basic for Applications
**VHBPR** Very High Bypass Ratio

## Symbols

$H$ Altitude
$L/D$ Lift to Drag Ratio
$\dot{m}_0$ Engine Mass Flow Rate
$M_{cr}$ Cruise Mach Number
$S$ Wing Area
$T_{sls}$ Sea/Level Static Thrust
$V$ Velocity
$\lambda$ Taper Ratio
$\Lambda_{c4}$ Sweep Angle of Quarter-Chord Line
$\pi$ Pressure Ratio
$\tau$ Temperature Ratio
$\tau_t$ Stagnation Temperatures Ratio of Low to High-Pressure Turbine