A JAVA-BASED FRAMEWORK FOR AIRCRAFT PRELIMINARY DESIGN

WING AERODYNAMIC ANALYSIS MODULE, LONGITUDINAL STATIC STABILITY AND CONTROL MODULE

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Abstract. The purpose of this work is the development of ADOpT (Aircraft Design and Optimization Tool) and its reference library JPAD, a java-based framework conceived as a fast and efficient tool useful as support in the preliminary design phases of an aircraft, and during its optimization process. The principal focus of the library is the overall aircraft model, conceived as a set of interconnected and parameterized components: wing, horizontal and vertical tailplane, fuselage, nacelles, and the propulsion system. The input is an XML file which recalls other XML files each of which manages the aircraft components data as shown in Figure 1. This choice is made in order to simplify the composition of the input for the user. The aim of this work is to create and to make operative the modules for the analysis of Lift, Drag and for Longitudinal Static Stability on an aircraft, including the non-linear effects.

Keywords Aircraft design, Java, Longitudinal Static Stability, JPAD

1 Introduction

The conceptual and preliminary design phases play a key role for the best development of future transport aircraft. A software framework that could help in finding a configuration which satisfies several basic requirements, and eventually a constrained optimum, is an essential tool for academic and industrial aircraft design activities. Since in the conceptual and preliminary design phases a lot of different configurations have to be analyzed in a relatively short time. For this reason, the aircraft design is projected to the utilization of new analysis tools that hold a main role in the design and optimization process.

A modern preliminary aircraft design tool should be characterized by a certain level of accuracy and reliability (even using very fast and simple semi-empirical procedures), by short computational time, by the capability to perform a multidisciplinary analysis, and by the possibility to perform some mathematical optimization processes (often constrained optimization) with modern optimization algorithms (i.e. genetic algorithm). These are the guide-lines followed during the development of JPAD.

The software presented in this work is completely written in Java. The choice of the programming language was driven by several considerations. First of all, the language should be widely supported; this to avoid the case of many valid aircraft design applications and libraries that became obsolete due to the aging of the programming language used to build them. Furthermore, the language is object oriented; this is very useful in order to manage an aircraft formed by components.

Each module (package) can be programmed quite independently so that it is relatively easy to divide the work among several programmers. This is essential since the amount of classes and calculations needed to abstract, manage and analyze the entire aircraft is very large.

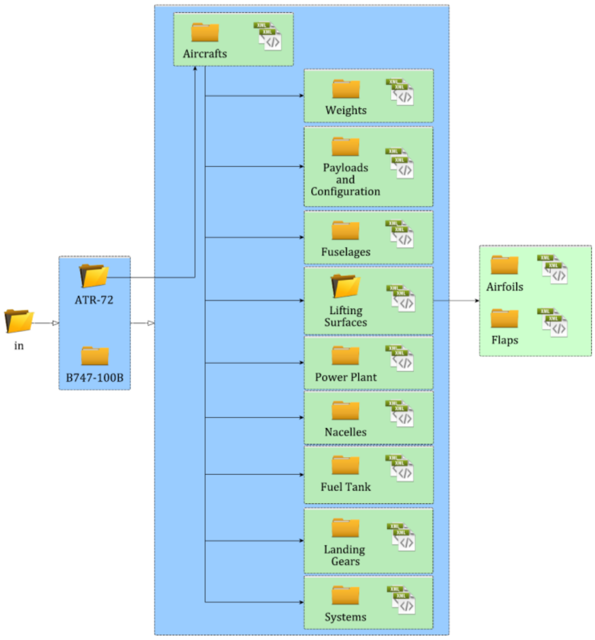

Figure 1 : Input folder organization.

Currently, the software is able to estimate the aircraft weight breakdown, the center of gravity location, the main aerodynamic parameters, the stability derivatives, the main performance and the longitudinal static stability. A GUI is considered as future work and is still in development (Figure 2). All these types of estimates can be usually performed using several interchangeable analysis methods. Extensive work has been performed during the early development stages to validate all the results returned by analysis modules of the application.

In this work the used methods for the analysis of Lift, Drag and for Longitudinal Static Stability will be explained and the obtained results will be presented.

The implemented methods are shown in the Section 2. In order to validate the code, a several number of analysis are made. The chosen aircraft are two: a regional turboprop similar to ATR 72 and a transport jet similar to BOEING 747-100B to consider the sweep effects. These applications shows that the results are in agreement with experimental data or flight manual.

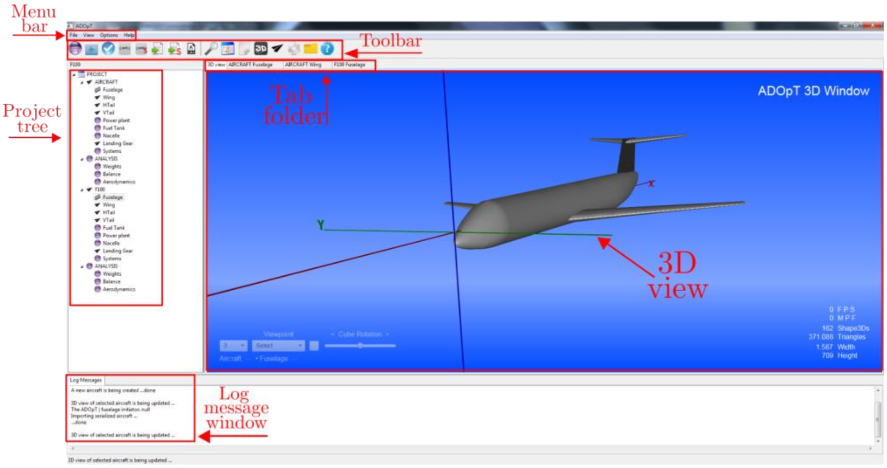

Figure 2 : ADOpT GUI.

2.1. Wing Lift Characteristics

In order to achieve the complete curve of lift coefficient, it is necessary to obtain the following parameters (see Figure 3).

1. Zero-Lift Angle (α_{0L})
2. Lift Coefficient slope ($C_{L\alpha}$)
3. End of Linearity Angle (α_w^*)
4. Maximum Lift Coefficient ($C_{L\ max}$)
5. Stall Angle of attack ($\alpha_{w,stall}$)

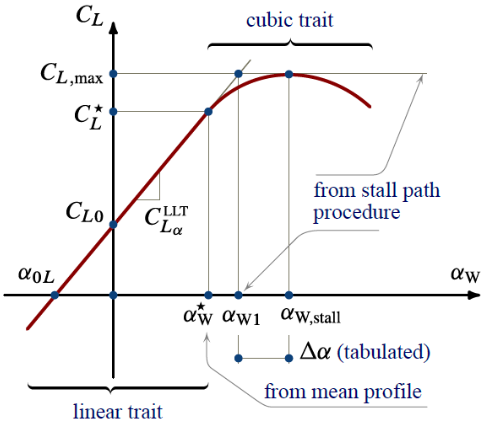

Figure 3 : C_l vs. α curve.

The majority of these parameters are obtained starting from the wing lift distribution that is calculated using the Nasa-Blackwell method [1] which provides the loading distributions over the lifting surface. Mach number effect is introduced through a Prandtl-Glauert correction and the maximum lift coefficient is calculated using the stall path method.

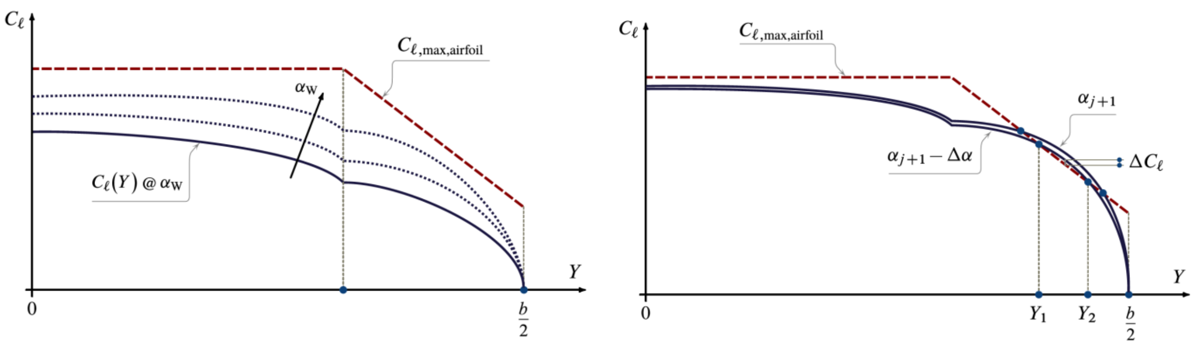

Figure 4 : $C_{l\ max}$ evaluation. Stall Path.

The practiced procedure is the following:

1. For each value of an alpha array, the load distribution is calculated using the Nasa-Blackwell method. The distribution of C_{l_max} is known.
2. At $\alpha = \alpha_j$ the load distribution curve intersects for the first time the C_{l_max} curve of the airfoils.
3. For each $y > y_1$, along y axis (where y_1 is the station of first intersection) is evaluated the difference between the local C_l and C_{l_max}.
4. A new Δα, used in the following step, is evaluated until the maximum difference between the maximum local C_l and C_{lmax} is smaller than the required accuracy.

At this point all elements are available in order to draft the C_L vs. α curve. The linear trait is evaluated using the equation of straight line. In order to plot the non-linear trait is used a cubic function. In fact, in this zone we have four conditions:

1. Pass to α^* and C_L^*
2. The derivative in α^*, C_L^* is $C_{L\alpha}$
3. Pass to α^* and C_L^*
4. The derivative in α^*, C_L^* is zero. Here there is the maximum of the curve.

The lift estimation classes are organized as shown in the Figure 5.

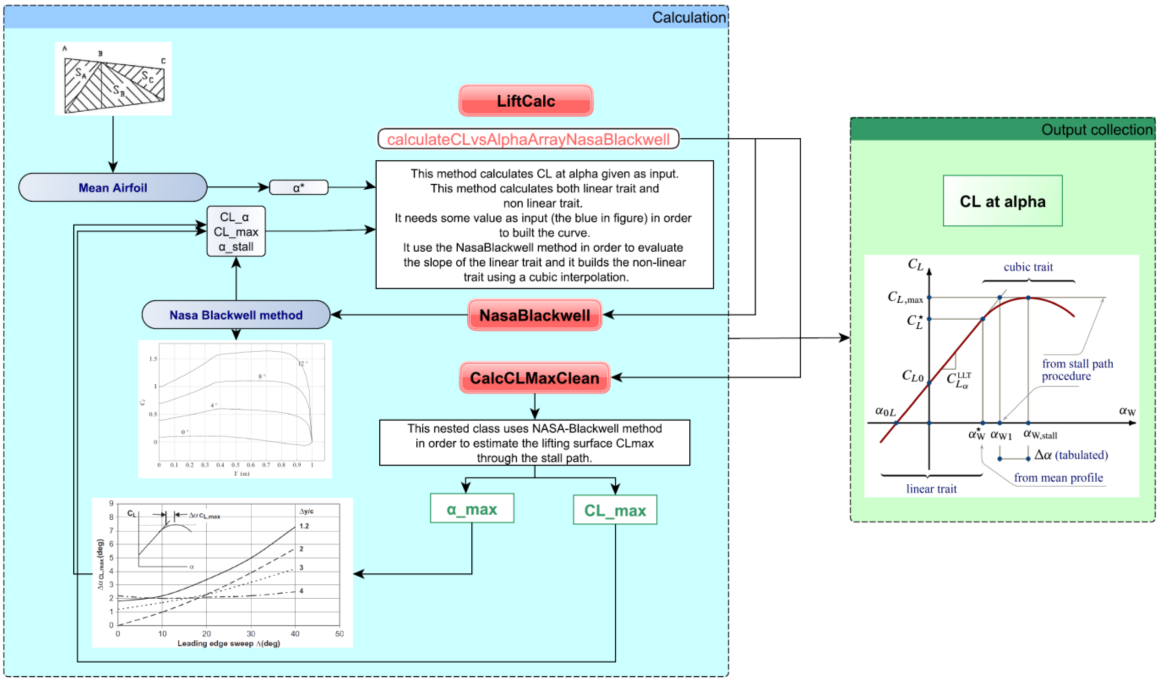

Figure 5: Flow chart of lift estimation classes.

2.2. Wing Drag Characteristics

There is not a single classification of the drag but, dependent on the purpose of the work, the drag may be broken down in different way. Assuming the breakdown shown in Figure 6, in JPAD is possible to use different methods in order to evaluate the drag coefficient of a wing and of the entire aircraft.

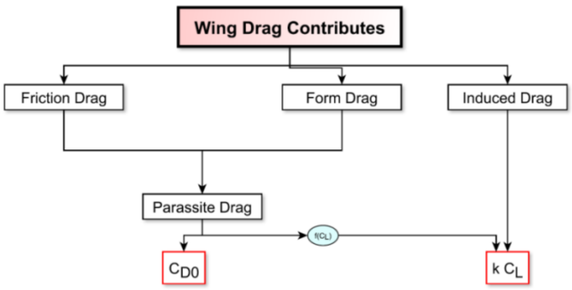

Figure 6: Used break down for the wing drag.

It is possible to define the wing drag coefficient as follows

$$C_D = C_{D0} + K\ C_L^2 \qquad (1.1)$$

Part of the drag depends on the lift coefficient, C_L, and it is called induced drag, while the other part is constant. The wing drag polar can be approximates as a parabola where the C_{D0} is the origin.

It is possible to evaluate the parasite drag starting from the airfoils, meanwhile the contribution that varies with the C_L is calculated from the induced angle of attack.

The practiced procedure is the following:

1. First of all, the load distribution at a given angle of attack is calculated.
2. Fifty points are defined along the semi-span.
3. The aerodynamic characteristics of the intermediate airfoil is estimated for each point.
4. Starting from the C_l and using a parabolic approximation for the drag polar, the C_d is calculated with the equation (1.1).
5. Known the drag distribution it is possible to calculate the drag coefficient of the lifting surface integrating.

The induced drag introduces tridimensional effects on the drag estimation.

$$C_{D_i} = C_L \alpha_i \qquad (1.2)$$

Equation (1.2) has been used to evaluate the induced angle of attack along the semi-span following the procedure describe below.

1. The load distribution at a given angle of attack is calculated.
2. The distribution of induced angle at a given angle of attack is calculated.
3. Fifty points are defined along the semi-span.
4. The lift coefficient at each station corresponds to local profile and it is possible to evaluate the drag coefficient.

$$C_{di} = C_l\ \alpha_i \qquad (1.3)$$

5. Known the drag distribution it is possible to calculate the drag coefficient of the lifting surface integrating.

2.3. Pitching Moment Characteristics

In this section a procedure useful to evaluate the pitching moment coefficient of a lifting surface at a given angle of attack, is described in detail.

First of all, the pitching moment coefficient with respect to the point at a quarter of the mean aerodynamic chord has been calculated. Starting from these values, varying the angle of attack, it is possible to evaluate the position of aerodynamic center.

1. Fifty points are defined along the semi-span.
2. The aerodynamic characteristics of the intermediate airfoil is estimated for each point.
3. The lift coefficient is calculated with the local C_l vs. α curve for each airfoil at a given station. In this way it is possible to consider both the linear trait and the non-linear one.
4. The position of the center of pressure is calculated for each airfoil.
5. The arm between the local center of pressure and the point at a quarter of lifting surface MAC is calculated for each airfoil.
6. Finally, it is possible to evaluate the pitching moment about the point at a quarter of MAC at each station with the product between the lift force and the arm.

In order to evaluate the pitching moment of the fuselage in JPAD it is possible to use both the Multhopp method [2] and a fuselage pitching moment prediction method that has been developed at the Dept. of Industrial Engineering, University of Study of Naples Federico II, by numerical aerodynamic analyses performed with STAR-CCM+ [3]. Moreover, JPAD is able to take into account the effects of propeller and slipstream on airplane static longitudinal stability which can be significant.

2.4 Aircraft longitudinal static stability

All features shown in previous sections are incorporated in the JPAD module of longitudinal static stability, which is possible to execute for a given aircraft and a flight condition.

To calculate the aerodynamic characteristics of the tail it is necessary to obtain the local angle of attack. Due to the finite extension of the wing, the airflow behind the wing is deflected. So it is necessary to evaluate this deflection. The downwash gradient and the angle of downwash have been evaluated considering the distances between the horizontal tail and the vortex plane variable. In this way the downwash calculation turns out to be more accurate.

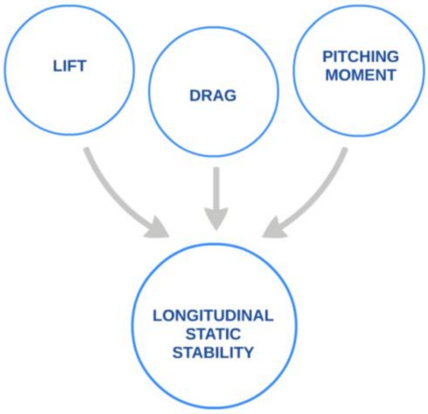

Figure 7: Flow chart of longitudinal static stability determination

The downwash equation are proposed in [4]. The distances in the downwash formula are variable and they are measured from the vortex shed plane. These distances have been calculated referring to the geometrical construction shown in Figure 8, estimating step by step the values of *r* and *m* (see Figure 8). The downwash gradient, in fact, depends on the angle of attack which depends in turn on the downwash angle. So in JPAD an iterative process has been implemented.

First of all, it is necessary to evaluate the geometrical distances m_0 and x_0, then it is possible to evaluate step-by-step the other distances which, fixed geometry, only depend with alpha. The process starts from a value of α_a= 0° and proceeds with an increase of angle of attack equal to Δα. The distances shown in Figure 8 are the following:

- x_0 → distance between the aerodynamic center of the wing and the aerodynamic center of the horizontal tail calculated along the x axis.
- m_0 → distance between the aerodynamic center of the horizontal tail and the horizontal line passing through the trailing edge of the airfoil root of the wing.
- *d* → distance between the trailing edge of the wing and the aerodynamic center of the horizontal tail. Considering the triangle BCD, it is possible evaluate the hypotenuse as follows:

$$d = \sqrt{CD^2 + BD^2} \tag{1.4}$$

where CD is the distance m0 defined before and it is possible to evaluate the distance BD

$$BD = x_0 - \frac{3}{4} c_r \cos(i_w) \tag{1.5}$$

- ψ → This is the angle between the distance d and the horizontal reference line.

$$\psi = \arctan\left(\frac{m_0}{BD}\right) \tag{1.6}$$

Starting from these geometrical values it is possible to evaluate the distances m and r for each angle of attack.

- $m|_i = d\sin(\psi + i_w - \alpha_{0L} - i\Delta\alpha + \varepsilon)$ (1.7)
- $x|_i = d\cos(\psi + i_w - \alpha_{0L} - i\Delta\alpha + \varepsilon) + \frac{3}{4}c_r\cos(-\alpha_{0L} - i\Delta\alpha + \varepsilon)$ (1.8)

For each step is preliminary defined a temporary value of ε, in fact the downwash angle depends on the downwash gradient which depends on the distances *m* and *x*, which depend, in turn, on the downwash angle.

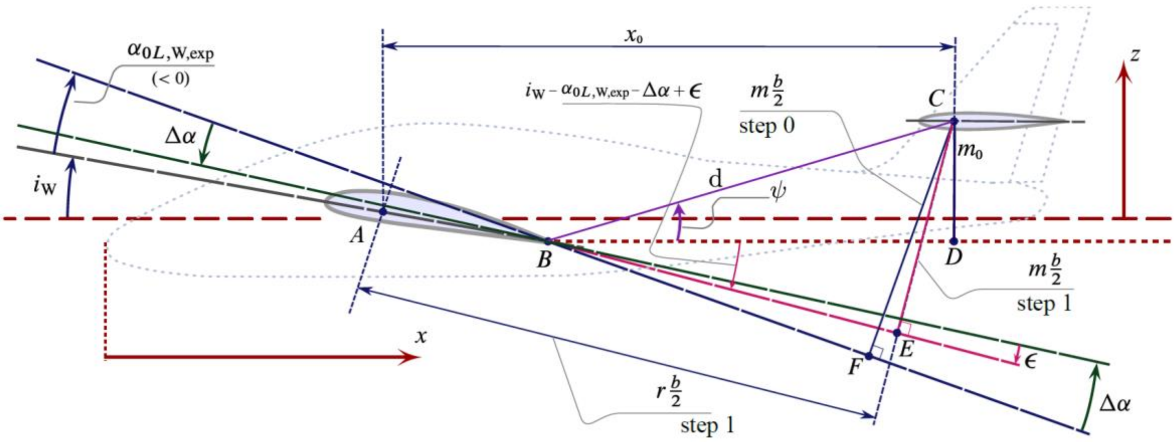

Figure 8 : Arm definitions for downwash gradient evaluation.

JPAD library has been implemented using the following process.

1. First of all, this method creates an array of absolute angle of attack starting from α=0° to α=20° with a step of 0.25°.
2. The results arrays are initialized (α_a, α_B, $\frac{d\varepsilon}{d\alpha}$, ε, m)
3. For the first step the state is the following:
    - $\alpha_a = 0$
    - $\alpha_B = \alpha_{0L} - i_w$
    - $\frac{d\varepsilon}{d\alpha}$ is the constant value
    - $m = d\sin(\psi + i_w - \alpha_{0L})$
    - $r = d\cos(\psi + i_w - \alpha_{0L}) + 0.75\, c_r\cos(-\alpha_{0L})$
    - $\varepsilon = 0$
4. Starting from the second step the process is iterative. For the generic step i:
    - $\alpha_a|_i = i\,\Delta\alpha$
    - $\varepsilon_{temp} = \varepsilon_{i-1} + \frac{d\varepsilon}{d\alpha}|_{i-1} \cdot \Delta\alpha|_i$
    - $m|_{temp}$, $r|_{temp}$, $\frac{d\varepsilon}{d\alpha}|_{temp}$ are calculated considering the temporary value of the downwash angle.
    - $\varepsilon_i = \varepsilon_{i-1} + \frac{d\varepsilon}{d\alpha}|_{temp} \cdot \Delta\alpha|_i$
    - $m|_i$, $r|_i$, $\frac{d\varepsilon}{d\alpha}|_i$ are calculated considering the new value of downwash angle.

- $\alpha_B = \alpha_{0L} - i_w + \alpha_a$

2 Application

All the following analysis will be carried out using two reference aircraft. This choice is made in order to avoid the collection and validation data phase for each analysis and make focus on the results. As mentioned, there are two default aircrafts in the code: a regional turboprop similar to ATR-72 and a turbofan similar to Boeing 747-100B whose main data are shown in the table below.

	ATR-72	**B747-100B**
Operating Conditions		
Altitude	6000.0000 m	10 000.0000 m
Cruising Mach number	0.4300	0.8300
Wing		
Surface	61.0000 m^2	511.0000 m^2
Æ	12.0000	6.9000
Span	27.055 49 m	59.3792 m
Taper Ratio	0.5450	0.2840
Root Chord	2.9186 m	14.6152 m
Mean Aerodynamic Chord	2.3198 m	9.6913 m
$Sweep_{LE}$	2.8390°	38.4290°
$Sweep_{C/4}$	1.3997°	35.4999°
t/c_{max}	0.1675	0.1292
C_{D0}	0.03170	0.01820
Oswald Factor	0.7585	0.6277
Airfoil type	Conventional	Modern Supercritical
Horizontal Tail		
Surface	11.7300 m^2	136.6000 m^2
Æ	4.5550	3.5700
Span	7.3095 m	22.083 07 m
Taper Ratio	0.5700	0.2650
Root Chord	2.044 30 m	9.7798 m
Mean Aerodynamic Chord	1.6450 m	6.8835 m
$Sweep_{LE}$	3.4410°	38.2250°
$Sweep_{C/4}$	0.0000°	32.0003°
t/c_{max}	0.1500	0.1500

Table 1: Aircrafts geometrical data.

In the Figure 10 is shown the effect of the Mach number on the lift coefficient, meanwhile in the Figure 101 is illustrated the effect of high lift devices on the lift coefficient curve.

Station	Airfoil	Reynolds Number	CL_{max}
Root	NACA 23018	$6.28 \cdot 10^6$	1.65
Kink	NACA 23018	$6.28 \cdot 10^6$	1.65
Tip	NACA 23015	$4.41 \cdot 10^6$	1.7

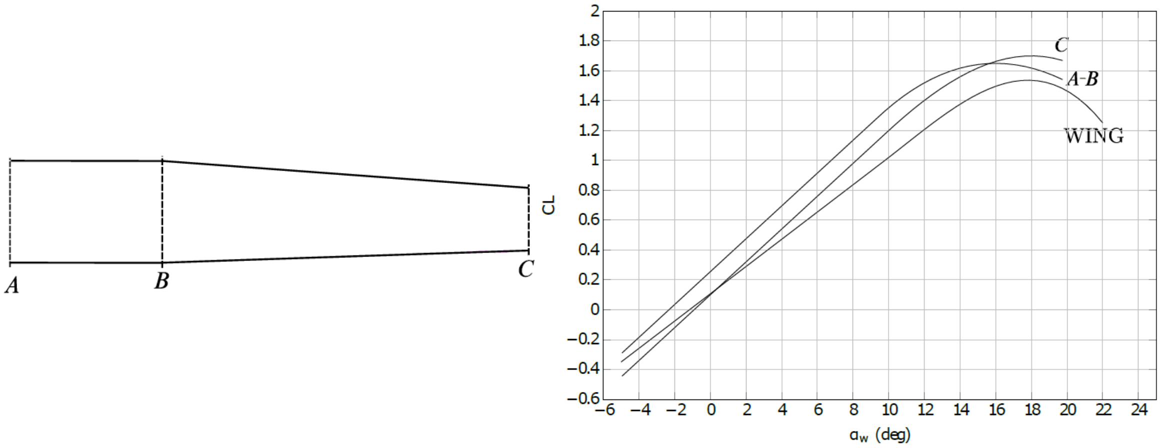

Figure 9 : 2D and 3D lift results for regional turboprop. M=0.2.

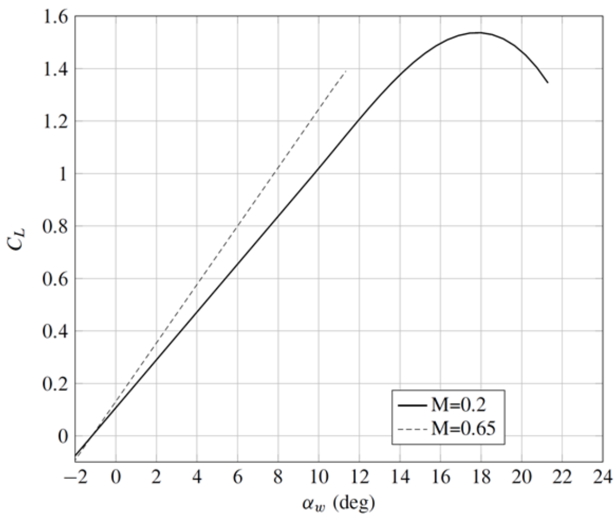

Figure 10 : Regional turboprop, variation with Mach number.

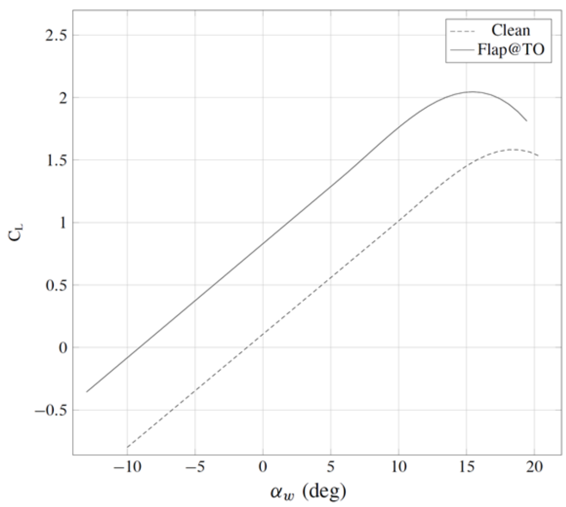

Figure 11 : Regional turboprop lift curve with and without flaps deflected in take-off configuration.

With the developed modules it is possible to execute an aerodynamic analysis on an isolated wing or on an aircraft evaluating the $C_{L\ max}$ using the stall path and drawing the complete curve of CL vs. alpha. It is also possible to evaluate the fuselage effects on wing lift and draw the lift curve with high lift devices. As shown in Figure 9, it is possible evaluate the lift curve both of an airfoil and of a wing.

Starting from 2D data of airfoils and the local induced angle of attack, it is possible to evaluate the parasite and induced the drag of a lifting surface (Figure 13). The high-lift devices effect on drag has been considered as shown in Figure 12.

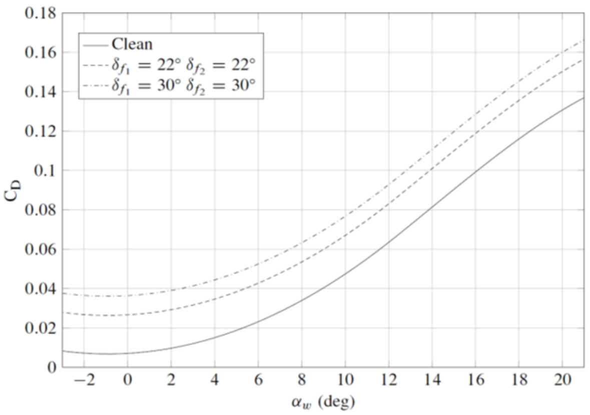

Figure 12: Drag coefficient of the wing with flap deflections Regional turboprop. M=0.4

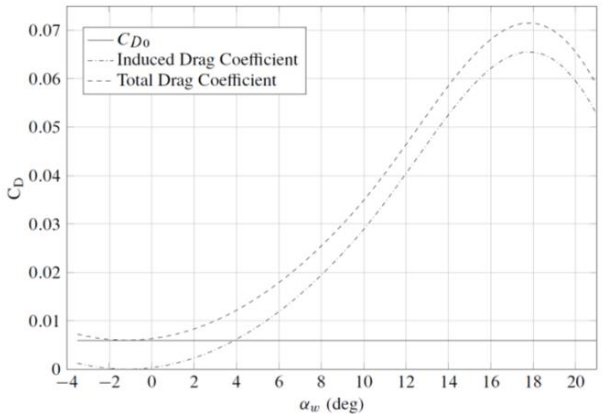

Figure 13: Drag coefficient components of the wing. Regional turboprop. M=0.4

The differences between the constant downwash and the non-constant one show that for high values of angle of attack there is a significant difference between these values, which is evident in Figure 14.

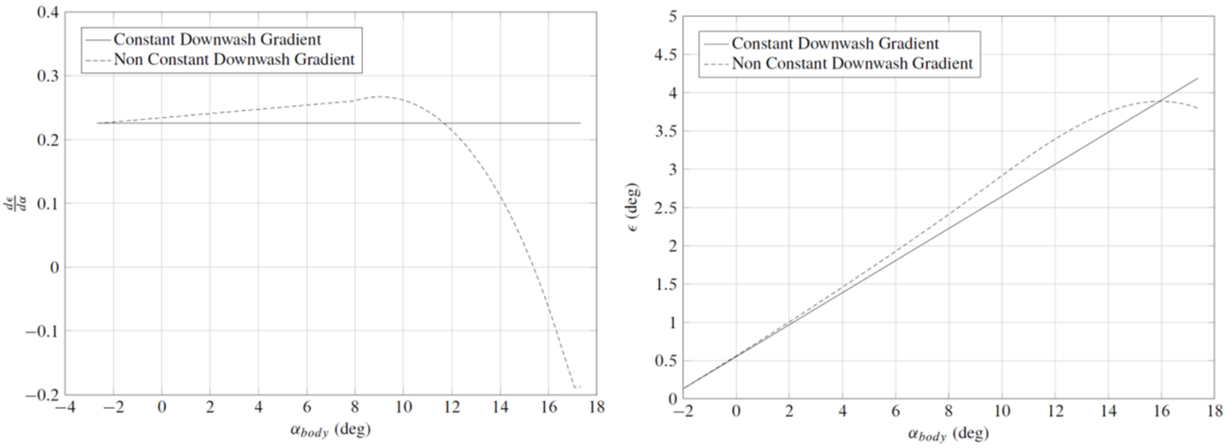

Figure 14 : Variability of downwash angle and downwash gradient. Regional turboprop, M=0.4.

All these features are incorporated in the calculation of longitudinal static stability that is possible to execute for a given aircraft and a flight condition. The stability calculation considers also the propulsion effects, the fuselage pitching moment effect, and the pendular stability due to the drag (Figure 16).

Using JPAD it is possible to evaluate the pitching moment of aircraft components and of the entire aircraft as shown in Figure 15, Figure 17 and Figure 19.

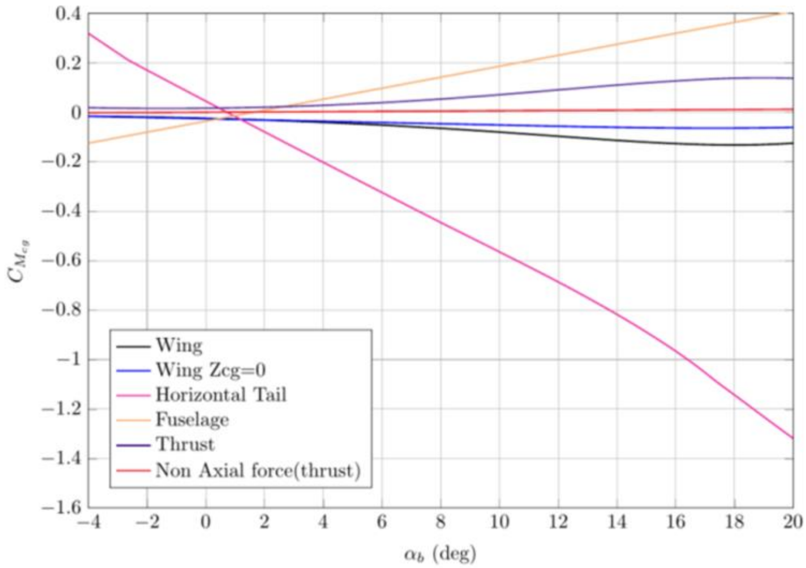

Figure 15: C_M respect to CG vs. α_b of aircraft components. Regional turboprop, cruise condition.

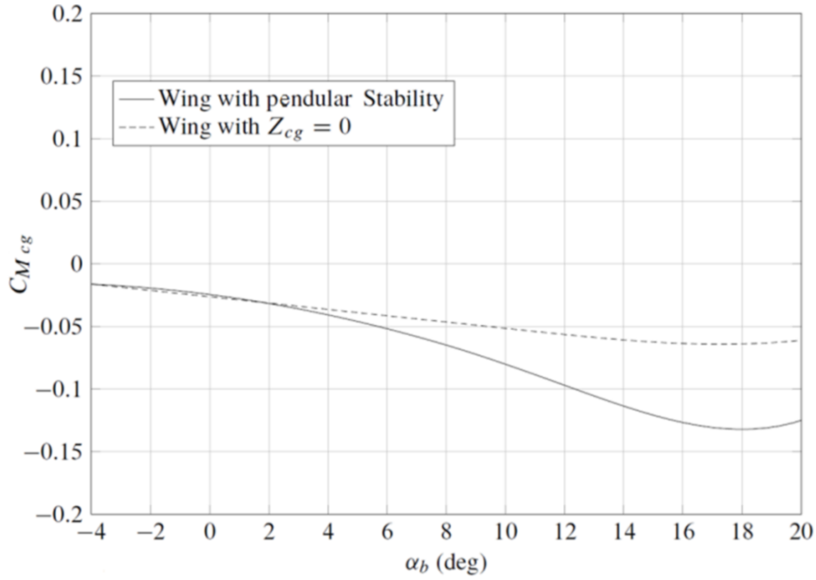

Figure 16 : : $C_{m\,cg}$ vs. α_b for the wing. Comparison with and without pendular stability. Regional turboprop. Cruise Condition.

In order to evaluate the lift coefficient of the entire airplane it is possible to consider it as consisting of the following parts[5]:

- Wing and Fuselage
- Horizontal Tail
- Canard

It is important to consider the effective angles of attack in which the surfaces work. This is made considering the angles of incidence of the lifting surfaces and the downwash angle aft of the wing. A horizontal tail and a canard may be equipped with a trailing edge control surface.

So in order to evaluate these contributes it is important to know the angle of deflection of these control surfaces (δ). The elevator can be considered as a plain flap.

All of these contributes return the global lift curve of the airplane (Figure 18).

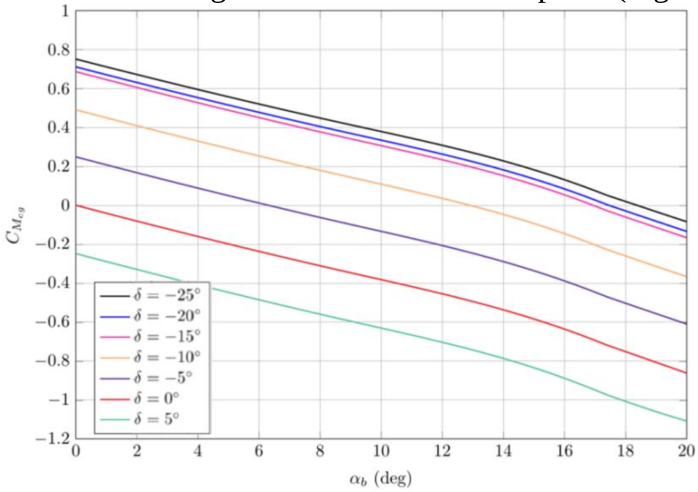

Figure 17 : C_M cg tot vs. α_b with elevator deflection. Regional turboprop. Cruise condition.

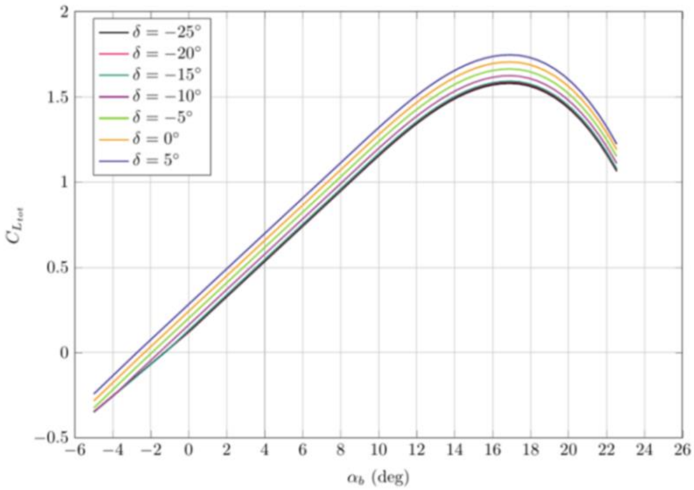

Figure 18: $C_{L\ tot}$ vs. α_b with elevator deflections. Regional turboprop. Cruise condition.

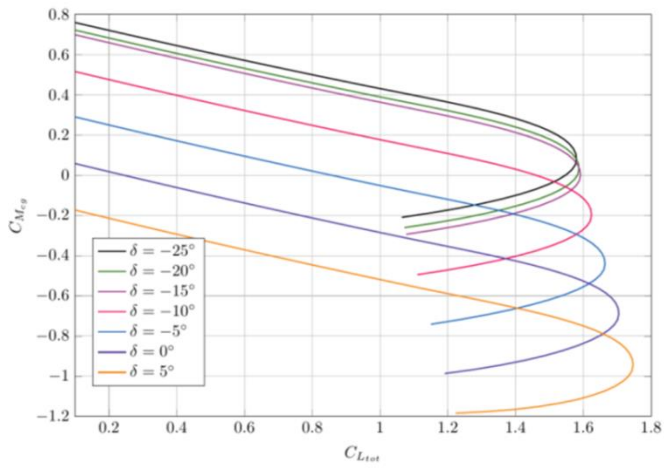

Figure 19 : C_{Mcg} vs. C_{Ltot} with elevator deflections. Regional turboprop. Cruise condition

Using JPAD it is possible to estimate the required elevator deflection to balance.

Furthermore, it is possible also to find the aerodynamic center of the aircraft, or, as it is usually called, the neutral point, by setting the derivative of the moment coefficient with respect to angle of attack equal to zero (Figure 20).

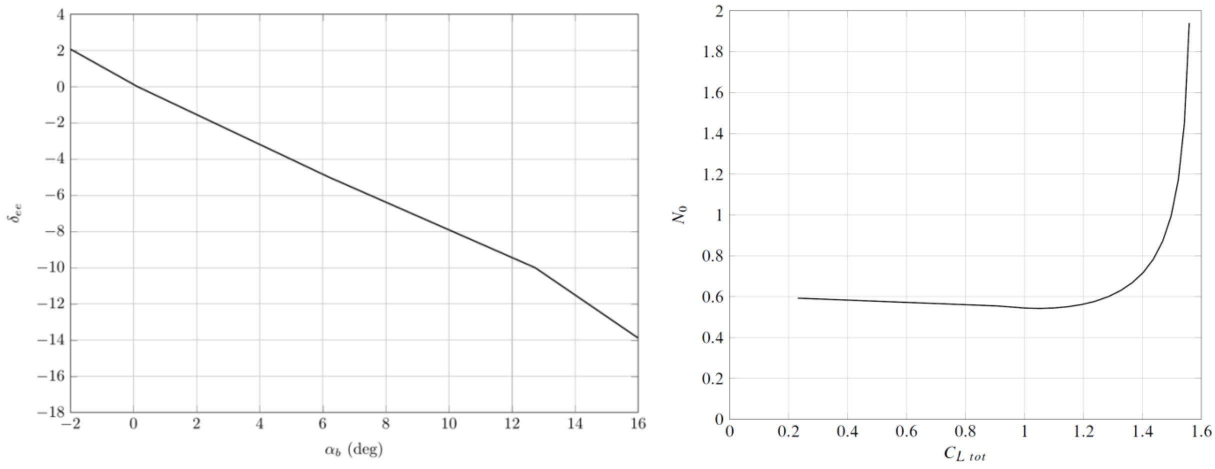

Figure 20 : δ_{ee} vs. α_b stick fixed (left), Neutral Point, stick fixed (right). Regional turboprop. Cruise conditions.

All the previous analyses have been made also on a TurboJet Aircraft with a significant sweep. In this section the main results for the Transport jet are shown, in order to underline the functionalities of the library also for a swept wing.

In the Figure 21 is shown the 2D and 3D results for Transport jet similar to Boeing 747-100B. In the Figure 22, meanwhile, is shown the stall path of the mentioned aircraft where the load distribution is calculated using the Nasa-Blackwell method.

Station	Airfoil	Reynolds Number	CL_{max}
Root	similar to BAC root 747	$3.67 \cdot 10^7$	1.7
Kink	similar to BAC kink 747	$2.18 \cdot 10^7$	1.73
Tip	similar to BAC tip 747	$9.53 \cdot 10^6$	1.82

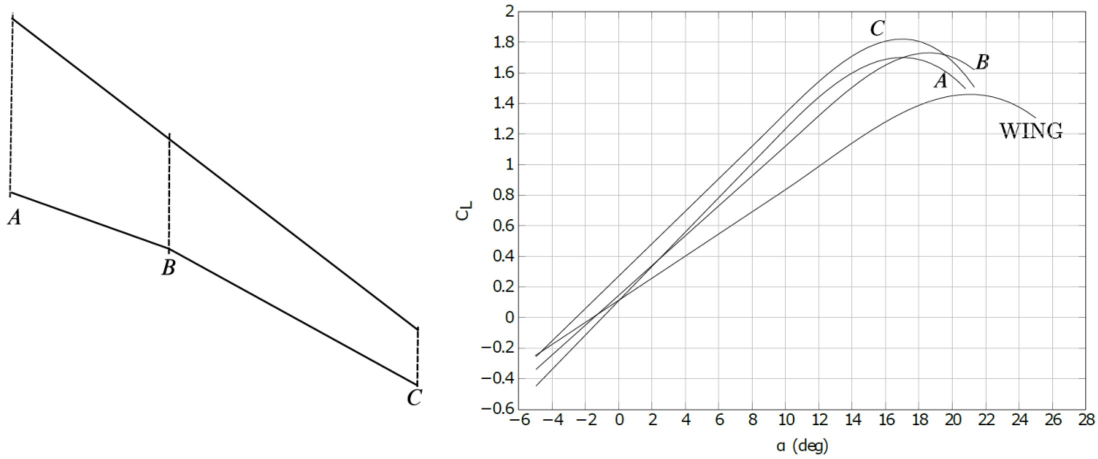

Figure 21: 2D and 3D lift results for Transport jet M=0.8.

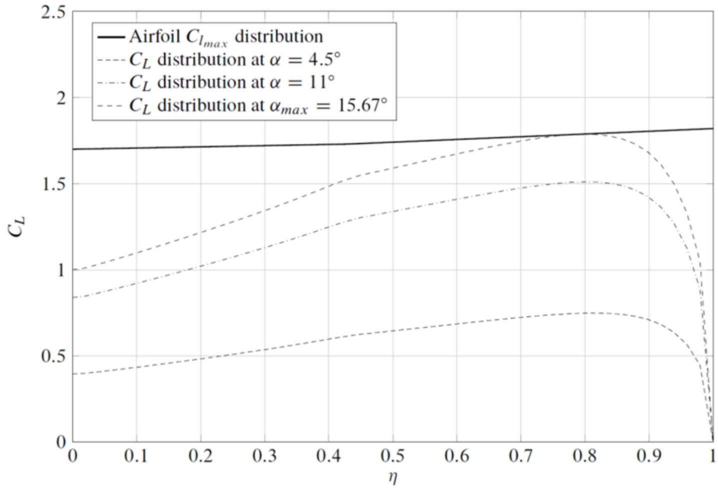

Figure 22: Stall path for Transport jet M=0.8.

With the JPAD library is also possible to evaluate the pitching moment coefficient of the wing respect to a generic point or respect to the aerodynamic center as shown in Figure 23 and Figure 24.

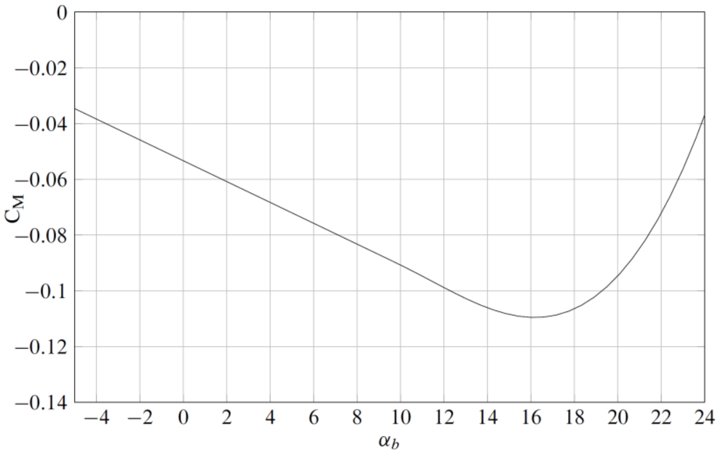

Figure 23: Mach 0.7. Pitching Moment Coefficient of the wing respect to a quarter of MAC. Transport jet.

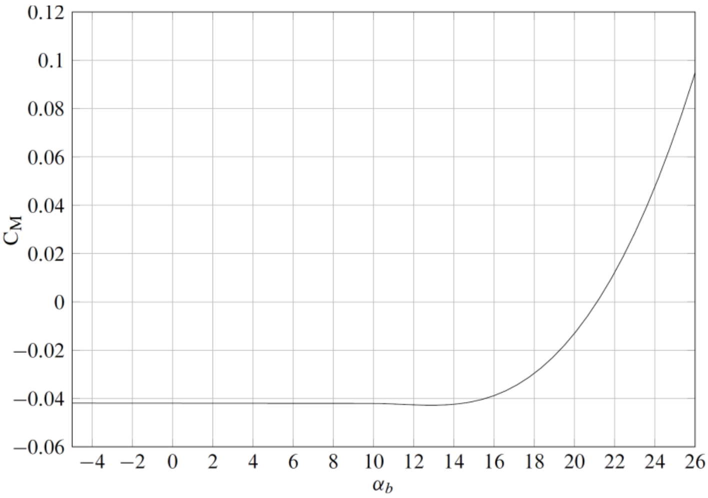

Figure 24: Mach 0.7. Pitching Moment Coefficient of the wing respect to AC= 0.308. Transport jet.

3 Conclusion

An aircraft design and optimization desktop application written in Java, and its functionality, has been introduced. The adoption of established software engineering practices, the use of advanced development tools, and concurrent development enabled the developer team to build a feature-rich application in a relatively short period of time. As of its design, the application is easily maintainable and extensible. The software is still growing and the choice of Java language was really helpful. In particular, being Java a pure object oriented programming language, it greatly encourages and simplifies modularization. Each module (package) can be programmed quite independently so that it is relatively easy to divide the work among several programmers working simultaneously or one after the other. The application, moreover, can be easily integrated into a comprehensive aircraft optimization cycle. As all analysis modules inside the JPAD will be completed and tested, the final purpose of the code will be to allow users to define a certain numbers of macroscopic geometrical parameters, along with a given objective function, and to receive as output the best set of the previous parameters which suits the wanted objective. These future targets will make the software able to carry out an analysis of an aircraft during its preliminary design phase in a fast and flexible way.

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