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Multidisciplinary design optimization applied to the conceptual design of a small unmanned aerial vehicle

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1. Abstract
The use of UAV aircraft has been increased in many sectors of society such as military defense, public security, search and rescue, remote sensing, agriculture control among others. This work develops a multidisciplinary optimization methodology to create the conceptual design of a small UAV, involving the areas of aerodynamics, structures and stability. The optimization, implemented in the commercial software modeFRONTIER, analyses several configurations, looking for an aircraft with less mass, and that meets the project restrictions. The results are compared to a previously designed prototype, which was established as a reference model, seeking to reduce its mass and improve their characteristics.
2. Keywords: UAV, multidisciplinary optimization, conceptual design, modeFRONTIER.

3. Introduction and Problem definition
UAV, unmanned aerial vehicle, is a term used to describe any type of aircraft that does not require a pilot aboard. The UAVs can be remote controlled aircraft, or can fly autonomously based on pre-programmed plans flight, or more complex dynamic automation systems [1].The design concept of an unmanned aerial vehicle was first developed in the American Civil War and latter was also applied in World War II by Japan and United States. Since then, this kind of tool has been improved, being employed not only for military or commercial applications, but also for the public and government sectors in air traffic control, agriculture, safety, among others [2]. It is expected that the worldwide market of UAV's will reach the mark of US$ 13.6 billion by 2014 [3]. The design of an aircraft involves several areas that are interconnected. This is an iterative project and is divided into three phases, conceptual design, preliminary and detailed.
The aircraft design is an extremely complex multidisciplinary process of determination of configuration variables to satisfy a series of mission requirements. For the designer, it becomes very difficult to foresee the consequences of a change in the variables in earlier phases of the design. The various parameters that determine the characteristics, aerodynamics, structural and stability of an aircraft have an interdependent relationship. Thus, the simultaneous variation of each parameter is required and is made possible by employing a process of multidisciplinary optimization, using genetic algorithms coupled to the tools of theoretical and numerical analysis. In this sense, the multi-objective design environment modeFRONTIER allows the integration of different computational software (any commercial or in-house code) into a common design environment, allowing the automatic run of a series of computations proposed by a selected optimization algorithm, until the specified objectives are satisfied.
At the end it is expected to develop a methodology that can be applied to the conceptual design of mini-UAVs resulting in a final configuration aircraft with the lowest structural weight, which meets the project requirements: be launched by hand, do not require airstrip, have a total load of up to 05 kg, maximum linear dimension of 3m, minimum range of 20 km, autonomy 60min minimum, be able to be transported, mounted and operated by a team of two people, enabling the installation of all equipment necessary for the performance of its function.

4. Methodology
As previously mentioned the modeFRONTIER is an environment of multidisciplinary optimization, which enables integration with several softwares. It is based on two main workflows, the flow of data and process flow. In Figure 1 the data flow occurs from the top down, starting in the definition of design variables and the process flow from left to right. After simulating the mounted configuration, the data flow follows to obtain the values of the responses of interest, verification constraints, and finally evaluating the objective function.

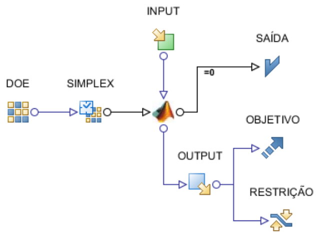

Figure 1: Generic flowchart

Figure 2 shows the flowchart developed for the conceptual design of the project involving the aircraft aerodynamic surfaces and structural components. The goal is to simulate quickly and efficiently a large number and variety of aircraft configurations. The input variables and their upper and lower limits are shown in Table 1.

Table 1: Optimized parameters definition

Input	*Lower boundary*	*Upper boundary*
Root Chord (m)	0,15	0,50
Tail arm (m)	0,5	1,5
Wingspan (m)	1,5	3
Wing aspect ratio	5	11
Wing taper ratio	0,3	1
Tapered Percentage of the wing	0,3	1
Vertical empennage aspect ratio	0,5	2
Horizontal empennage aspect ratio	2	4
Vertical empennage taper ratio	0,2	0,8
Horizontal empennage taper ratio	0,3	1
Vertical tail volume	0,005	0,05
Horizontal tail volume	0,4	1

The optimization program for the aircraft starts from an initial population, which uses optimization algorithm to vary characteristics of the aircraft. The program in MATLAB, **Desenho**, from the input variables, calculates all the data needed for the aircraft to be reproduced by AVL (Athena Vortex Lattice) estimated the mass of the wing, fuselage and empennages using volumetric densities and estimate parasite drag of aerodynamic surfaces, using the CBM (Component Buildup method) [4].
The next step is the simulation of the aircraft by AVL at AVL_STAB_CL_CD module to estimate the lift and drag of the aircraft, for different angles of attack, and obtain the necessary parameters for measuring the static stability of the aircraft. The AVL solves the equations of Laplace through the singularity distribution (horseshoe vortex) along the body, using criteria of impermeability, hard surfaces and Kutta condition. The method was chosen because it is fast, has good robustness, allowing multiple surfaces and takes into account the interference between these multiple surfaces. The AVL does not have a direct interaction with the modeFRONTIER, requiring the use of engagement scripts. As one of the AVL outputs, we have the derivative value dC_N/dB, which is restricted to be between 0015 and 0025, [5] and the value of the neutral point.
The program in MATLAB, **MS_Desempenho,** as from equations and aircraft characteristics, calculates the $C_{Lmáx}$, the stall speed and landing speed based on the total aircraft weight of 7.5 kg (maximum design total weight corrected by a safety factor of 1.5). It also calculates the static margin of the aircraft from the value obtained from the neutral point AVL, which is restricted to be between 0.05 and 0.25 [4].
In the next module, **load_control_avl**, a control analysis is made by AVL, where the pitch and yaw control surfaces trim is verified. To the pitch control surface, the horizontal stabilizer must balance the aircraft for the critical condition of $C_{Lmáx}$ and ground effect [5]. The yaw control surface must maintain the balance of the aircraft on landing, under $C_{Lmáx}$ and crosswind condition. In other module, **load_avl**, AVL simulates aircraft in cruise condition, resulting in values of C_L, C_d, C_m, for each panel along the wing.

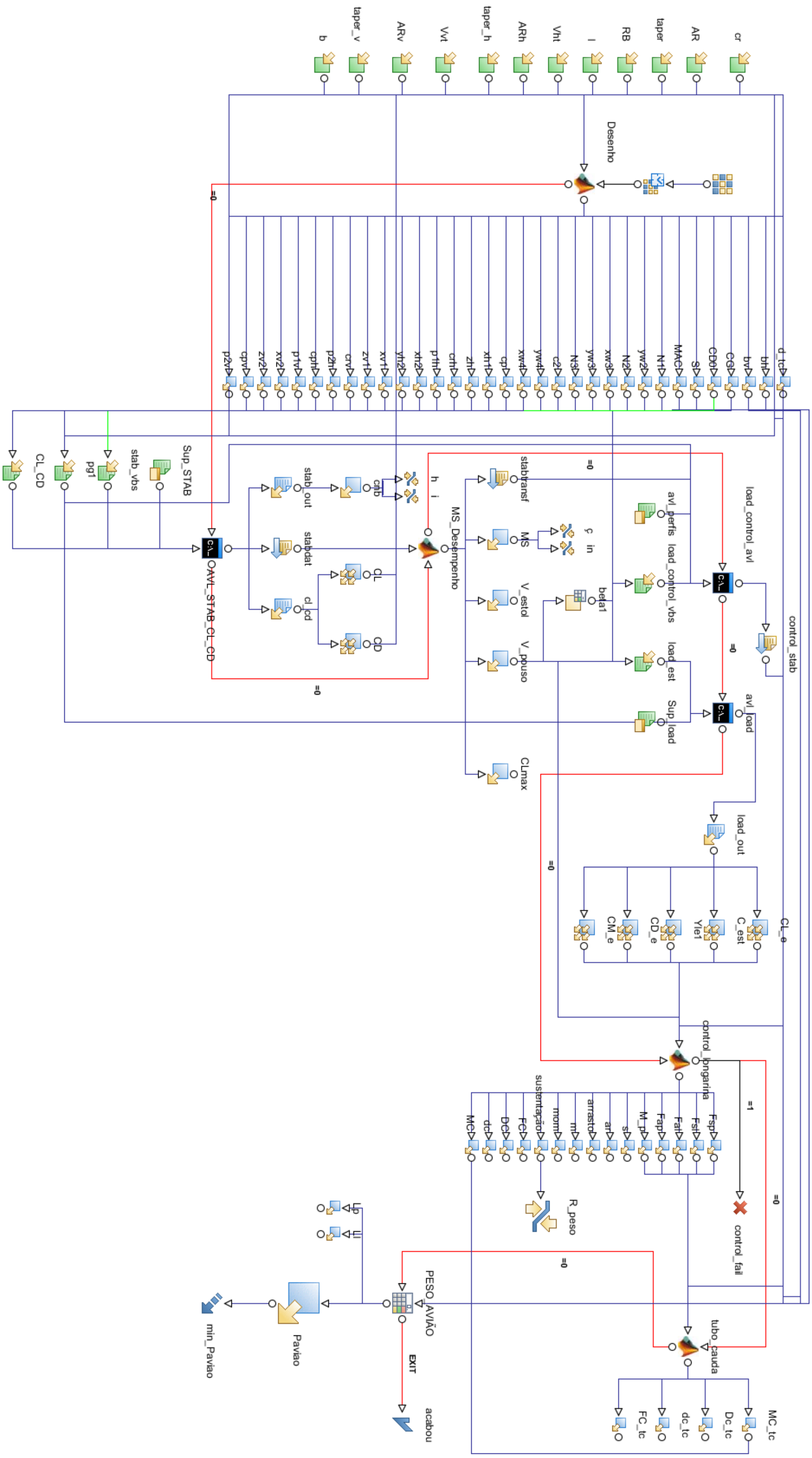

Figure 2: Conceptual project design flowchart.

The next step is a program in MATLAB, **control_longarina**, which calculates the forces of lift and drag along the wingspan as well as the aerodynamic moment, by then proceed to the design of tubular spar in carbon fiber / epoxy. The spar was treated as a cantilever clamped at the root of the wing, which varied the thickness of the composite tube, both restricted by its outer diameter smaller than the wing tip airfoil maximum thickness, in order to achieve the lightest tube that can withstand all possible stresses with a safety factor of 1.5 and a maximum deflection of 0.05 m, so that the interference on the wing aerodynamics characteristics has no significant effect. The failure criterion used was the Tsai-Hill, as one of the most accepted methods for composites and the method of superposition to find the maximum deflection at the tip of the wing.

Another function of this program is to import the maximum deflection of the control surfaces obtained in AVL. For deflections smaller than 30 ° [4], the lift and drag forces produced by the rudder and the elevator are calculated and transferred to the module, **tubo_cauda,** responsible for sizing the composite tail tube made of carbon fiber / epoxy, similar to the spar.

The latter process is responsible for calculating the final weight of the aircraft, and has as input the weight of the spar and and tail tube above dimensioned. In it are performed mass approximations of the wing and control surfaces, as well as the spar used in empennages. As output variable, we have the total aircraft weight, which is consequently used in the program's main objective is that its minimization. As restrictions beyond those imposed by the stability and control of aircraft, we also have one coming from the lift generated by the wing, which should be able to balance the aircraft weight of 7.5 kg stipulated as a condition of project.

The program implementation was conducted in two ways, one being the sole objective to minimize the weight and other multi-objective, aiming, beyond that previously mentioned, minimizing drag and maximizing lifting. These two approaches were used so that we can get more data for decision making regarding the final configuration of the aircraft conceptual design, since the modeFRONTIER provides optimization algorithms for specific mono-objective and multi-objective cases.

5. Results

5.1. Post-processing

After the execution of the three cases described in the previous chapter, the results were post-processed in the modeFRONTIER environment, where you can get a series of graphs relating the variables desired. In this particular case, the generated charts allow viewing of the objective function and how it relates to some design parameters. After analyzing the data obtained by the optimization program, the aircraft resulting from conceptual design will be designed in SolidWorks software for best viewing of the assembly.

5.2. Single-Objective optimization case

In the execution of the single-objective optimization, the algorithm used was the SIMPLEX. Within its settings you can change the maximum number of iterations and the residual value at the end of convergence. In all cases these values were 500 and 10^{-5}, respectively. As already stated, the SIMPLEX uses for initial analysis N +1 experiments, where N is the number of input variables, which for this case is 12. To define the initial population, we used the model Random Sequence, generating 50 individuals.

Figure 3 shows the convergence curve after 253 iterations for the objective function, whose final value was approximately 990 grams, and span over the iterations.

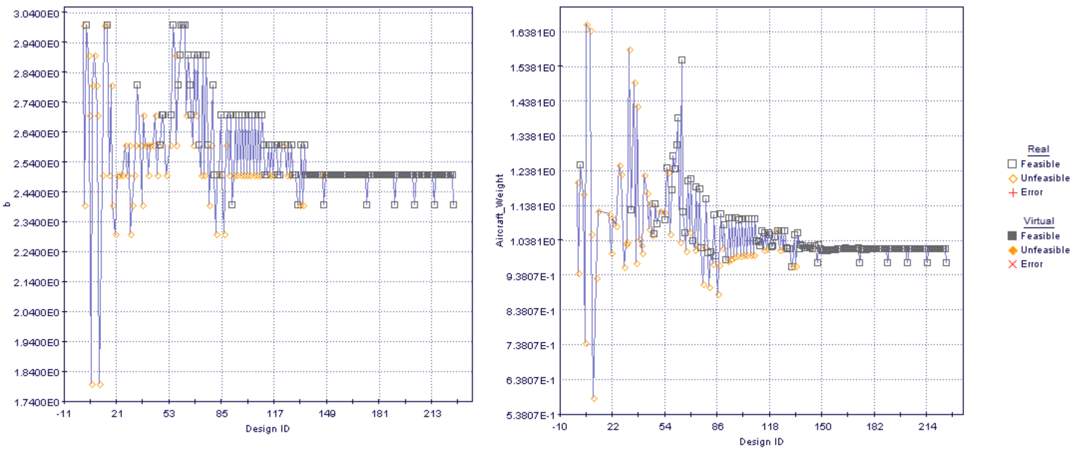

Figure 3: History chart

Figure 4 shows the scatter plot of the objective function as a function of lift. The green line represents the regression line between the data obtained. Individuals who are out of the restriction concerning minimum lift, are presented in the form of diamond in orange and those that are feasible, represented by a square of gray. Individuals who are below the line of convergence, are those that did not meet the other restrictions regarding the stability and control of the aircraft.
As the optimization algorithm for mono-objective cases analyzes only a fixed number of individuals, it is not possible to vary the initial population that the optimization algorithm will evaluate, in this context, the mono-objective optimization proved too restrictive with respect to the optimization algorithm settings. Thus it is not possible to evaluate the effect of different execution configurations of the program in the search for the global optimum. Unlike single-objective optimization, multi-objective allows a broader comparison in relation to execution settings, which is why it was also chosen to implement the proposed project objective.

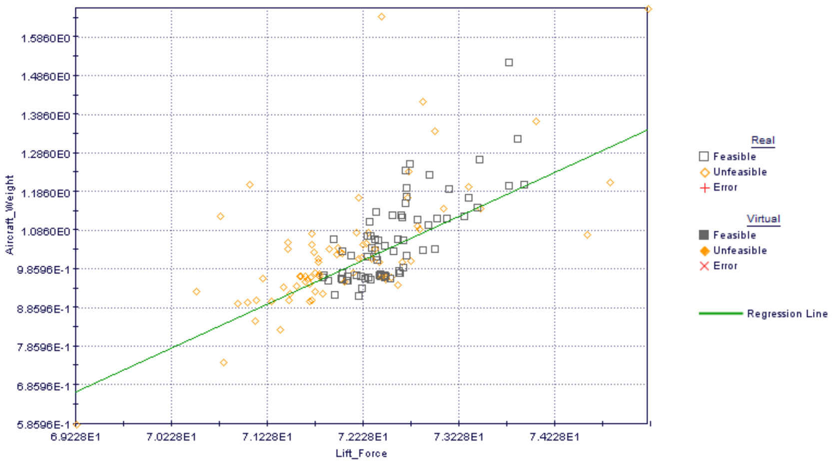

Figure 4: Scatter Chart

4.3. Multi-Objective optimization case
The first multi-objective optimization was executed with three goals, minimizing the mass of the airplane and the drag and maximizing the lift. In this case the only restrictions are those concerning the stability and control. The initial population was defined from the model Random Sequence, which allows a large dispersion of points between the design variables. The population consists of 100 individuals randomly spaced throughout the design domain. The Genetic Algorithm used was the MOGA-II, configured with the characteristics presented in Table 2.

Table 2: Configuration parameters

Generations Number	100
Probability of Directional cross-over	50%
Probability of Selection	5%
Probability of Mutation	12%
Num. of current design evaluations	2

Of the total 10,000, 456 aircraft failed due to a convergence problem and 6513 did not meet the restrictions. Figure 5 shows a scatter plot of the mass of the airplane versus lift, where aircraft in orange represent those unfeasible and the gray ones that are within the constraints.

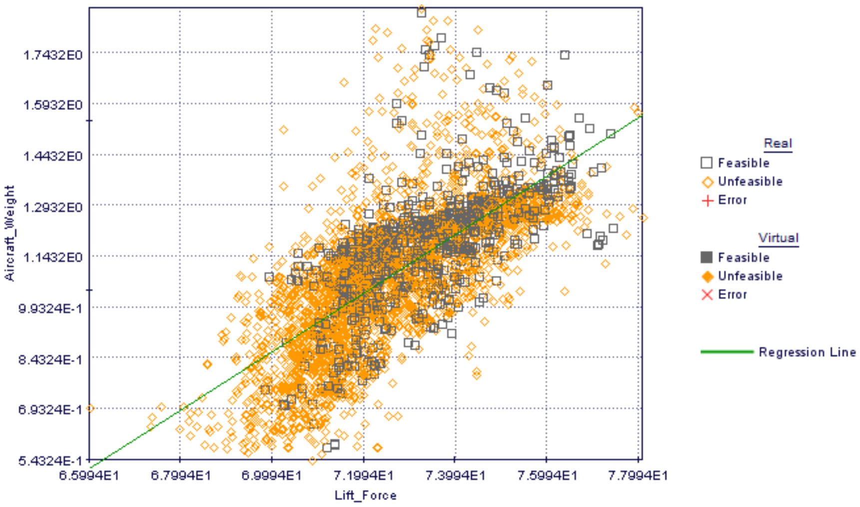

Figure 5: Scatter Chart

You can see that there is a wide dispersion of individuals below the minimum lift considered in the design, which can be explained by the absence of the restriction regarding the lift. Analysis of the chart is remarkable that in the absence of constraint, GA sought values that favor the reduction of weight and drag at the expense of lift. After this analysis, we considered relevant the addition of the restriction coupled to lift in an attempt to establish a parameter to guide the GA in finding the balance between lift and airplane weight.
After the new configuration, four optimizations were executed, each with different settings for the GA, MOGA-II. Table 3 shows a comparison between the settings for each case, and in all the initial population was generated with model Random Sequence.

Table 3: Configuration parameters in each case

Case	*A*	*B*	*C*	*D*
Number of Designs	50	100	150	80
Random Generator seed	400	666	800	0
Number of generations	100	100	80	100
Probability of Directional cross-over	60%	50%	80%	20%
Probability of Selection	8%	4%	7%	9%
Probability of Mutation	12%	10%	15%	20%
Num. of current design evaluations	4	4	3	2

For each case, scatter plots were generated relating to the objective function of maximizing lift and minimizing the weight of the aircraft. Figure 6 presents initially the graph for the case C and then the graph D case, these were chosen because they are the most discrepant in comparison to others in consequence of the greater difference between your settings. To this new optimization configuration we note the differentiation between individuals to the right of the value imposed by the restriction on the lift, mostly gray, indicating their viability and to the left in orange, indicating that they are unfeasible. Analyzing the most extreme individuals in the vertical axis, for both cases, you can see some similarities between them. At the upper limit for the airplane weight, both present values around 1900 grams. In the lower limit for the C case there is a large concentration of feasible experiments in the range of 700 to 800 grams, while for the D case there are only two individuals of which one with the lowest weight is approximately 750 grams.
What can be seen by examining the results for cases C and D is that the wingspan has a large contribution in the search for minimizing weight. As spar is the component with the most structural mass, genetic algorithm always seeks to minimize its value, and to achieve the constraint on the support, it increases the wing root chord, while increasing taper ratio, thus increasing the projected area of the wing. The same can be observed in the tail pipe. As the increase of its length brings a greater mass, the genetic algorithm seeks to minimize it, increasing the projected area of empennages in an attempt to succeed in the constraints of stability and control.

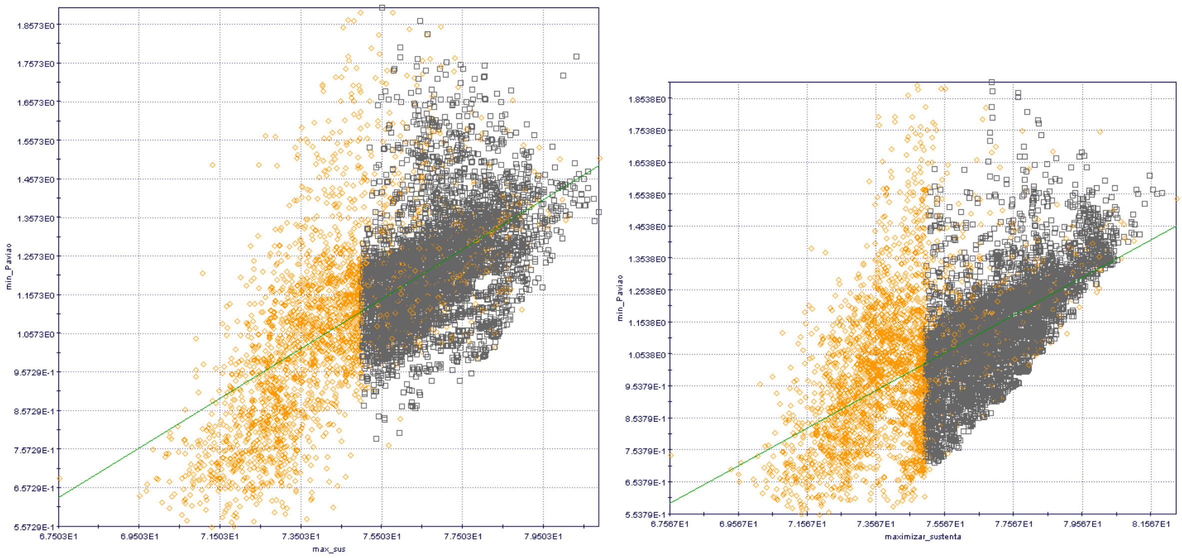

Figure 6: Scatter Chart cases C and D

To further analyze the influence of wingspan on the objective function, the graphs were plotted in bubble type, which relate three variables, two of them shown in the Cartesian axes, in this case lift force on the horizontal axis and wingspan on the vertical axis, and the third across the diameter of each circle representing the aircraft weight. Figure 7 shows a comparison of cases B and C, which are those with all different execution configurations, respectively. In a first observation emphasizes again the similarity between the limits found for the aircraft wieght in both cases. In case B we note that even for a wingspan of 1.8 meters we have an individual with a mass well above the others, that due to the fact of the length of tail pipe and root chord being close to the upper limit of each but specifically in this case, the ID 9961 with the individual who has values of 0.45 m and 1.38 m respectively.

By examining the graph is a clear relation of proportionality between the wingspan and lift force, which was expected, but the increase in wingspan brings a greater spar, both in length and in diameter and therefore a greater mass. Another factor that the program is not able to measure is the induced drag, which effect is reduced with an increase in the aspect ratio of the wing, being studied in the preliminary project.

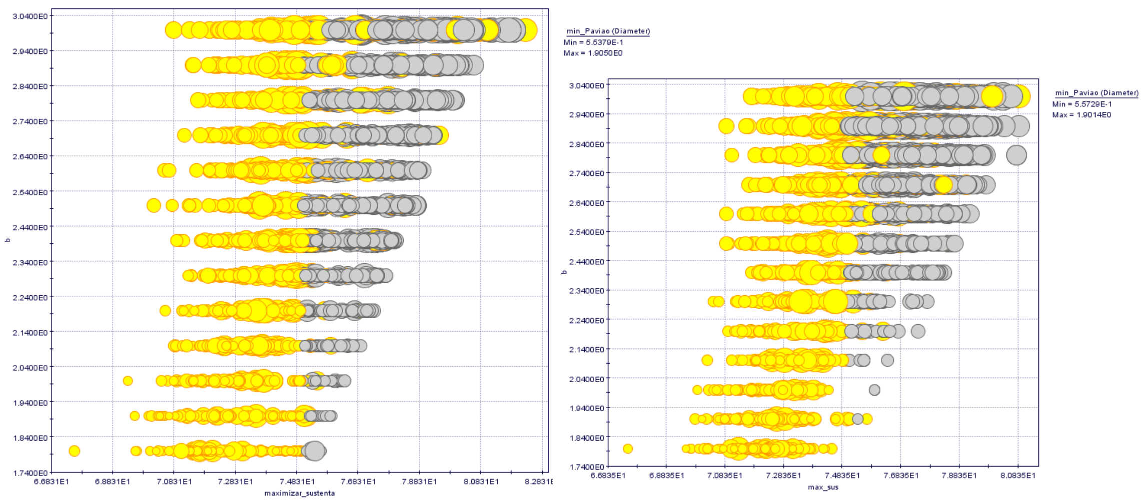

Figure 7: Bubble Chart cases B and C

To complete the information taken from the above charts, two more graphs were plotted in bubble type, with four dimensions, the three already mentioned plus a fourth dimension represented by the hue of the colors in each circle. Seeking to show the two lengths characteristic of the wing used as input variables, the cord in the root was used in the fourth dimension of each graph.

Figure 7 shows the two graphs, the first to case A and the second to case B. In these graphs are present only individuals that are possible within the constraints and can notice the contribution of the root chord for generating lift force and for the aircraft weight, which has similar limits around 700 grams inferior and 1900 grams superior.

For the case A the total population is 5,000, of these 987 have achieved the objectives within the constraints, for the case B this number reaches 3289, the total population of 10,000. For both cases it is possible to observe the agreement of the program, because as you increase the wingspan and root chord, the lift force and the aircraft weight follow the same trend.

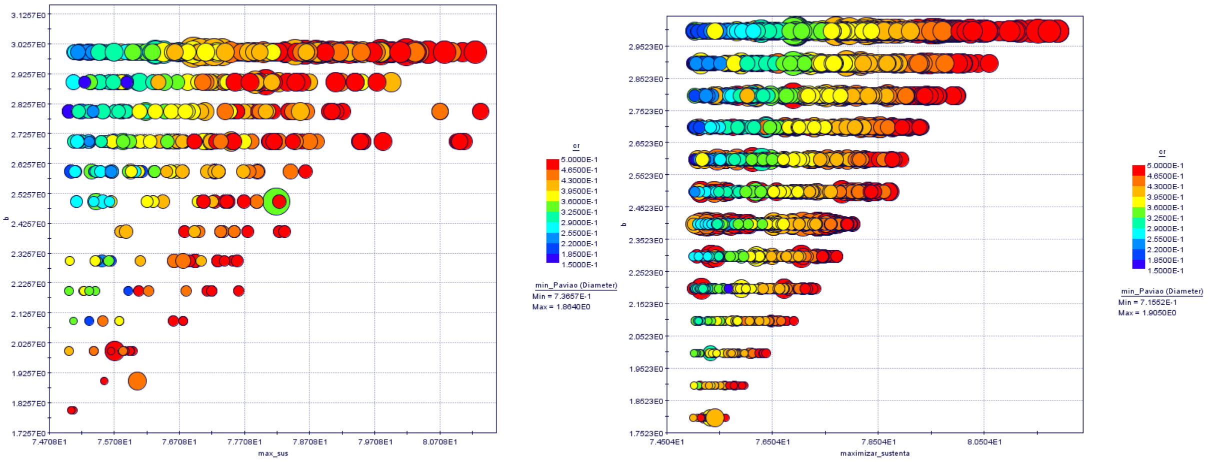

Figure 8: Bubble Chart cases A and B

4.4. Conceptual project aircraft configuration

After the execution and analysis of optimizations, the final configuration concerning the aircraft conceptual design was defined. To do this, in addition to the data collected in single-objective optimization for different design variables, was chosen an aircraft resulting from each case of multi-objective optimization. In choosing the optimal aircraft for multi-objective case, beyond the premises established by the optimization, we sought to evaluate those with characteristics more similar to a glider, as a high aspect ratio, based on a similar aircraft found in the market. After a weighting between the data analyzed, the configuration of the conceptual design has been defined and is available in Table 4, which also shows the data obtained by the optimization.

Table 4: Parameters comparation between cases

Input	*CASE A*	*CASE B*	*CASE C*	*CASE D*	*Conceptual design configuration*
Root Chord (m)	0,28	0,27	0,25	0,27	0,26
Tail arm (m)	0,71	0,65	0,83	0,77	0,75
Wingspan (m)	2,5	2,6	2,6	2,5	2,5
Wing aspect ratio	10,6	11,2	11,5	10,1	10,9
Wing taper ratio	0,64	0,58	0,51	0,53	0,55
Tapered Percentage of the wing	0,5	0,55	0,65	0,45	0,6
Vertical empennage aspect ratio	1,45	1,52	1,48	1,52	1,5
Horizontal empennage aspect ratio	2,2	3	2,0	2,1	2,4
Vertical empennage taper ratio	0,41	0,84	0,88	0,62	0,6
Horizontal empennage taper ratio	0,62	0,85	0,78	0,83	0,8
Vertical tail volume	0,0182	0,023	0,156	0,024	0,015
Horizontal tail volume	0,6	0,5	0,55	0,55	0,5

Figure 9 shows the aircraft isometric view withdrawal of the AVL program for the four cases listed in Table 4. Figure 10 shows a drawing, done in SolidWorks and rendered with PhotoView tool, of the conceptual design configuration of the aircraft.

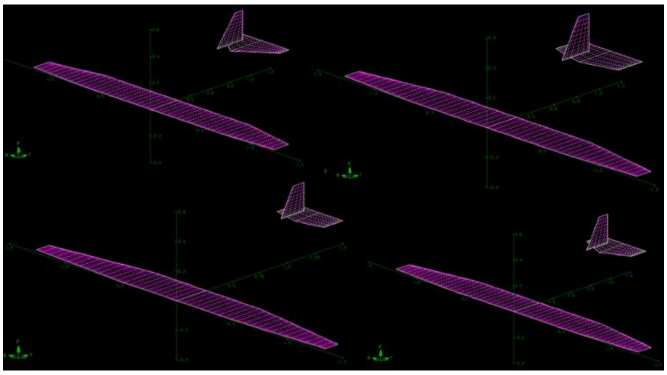

Figure 9: Isometric View from AVL

Figure 10: Conceptual project aircraft

5. Observations

Selected the conceptual design final configuration, the next step was to subject it to further analysis within the preliminary and detailed design of the aircraft. In the preliminary project the aerodynamic analysis included the deeper study of induced drag, since the optimization routine inside the modeFRONTIER was not able to measure it effectively. Likewise, the detailed design which served as the interface between the theoretical design and construction, so selecting the last fittings and materials, enabled the analysis of the position of the center of gravity and dynamic stability.

Upon completion of all phases of Aeronautical Design, we built a prototype aircraft, which can be seen in Figure 11. There were four pilot tests, where the aircraft to perform well, demonstrating good stability and response controls.

Figure 101: UAV prototype

6. Conclusions

The use of UAVs in several areas is a growing reality in the world. From this perspective, the present work aimed to study the multidisciplinary optimization applied to the conceptual design of an aircraft that meets the pre-established requirements.

Optimizations of the aircraft were performed for mono-objective and another multi-objective case, always seeking to minimize the aircraft weight, but ensuring that it is able to produce lift, capable of carrying a total mass of 7.5 kg. The results showed agreement between the two cases, and through these results a comparison was made between different aircraft configurations. However, the program is not able to submit the aircraft to a complete analysis, which is able to measure the induced drag, and the way the stall propagates on the wing, been both objects of study of the preliminary and detailed project.
The modeFRONTIER proved to be an environment quite interesting because it allows the integration of various analysis software used in aeronautical design. The routine developed proved to be useful, because through it is possible to analyze various configurations of aircraft, seeking one that best fits the objectives outlined in the project to make sure that you have an optimized project.

7. References

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