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Study of the development and verification of an integrated code for UAV design

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Grau en Enginyeria en Tecnologies Aeroespacials

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Table of acronyms and symbols

AVL	Advanced Vortex Latice
NACA	National Advisory Committee for Aeronautics
ACC	Air Cargo Challenge
ACC15	Air Cargo Challenge 2015
ETSEIAT	Escola Tècnica Superior d'Enginyeries Industrial I Aeronàutica de Terrassa
UPC	Universitat Politècnica de Catalunya
UAV	Unmanned Aerial Vehicle
NSGA	Non-Dominated Sorting Genetic Algorithm
VLM	Vortex Latice Method
C_l	Two dimensional lift coefficient
C_{df}	Two dimensional friction drag coefficient
C_{dp}	Two dimensional pressure drag coefficient
C_L	Three dimensional lift coefficient
C_{Df}	Three dimensional friction drag coefficient
C_{Dp}	Three dimensional pressure drag coefficient
C_T	Thrust coefficient
C_P	Pressure coefficient
I_0	Initial current intensity
R_0	Initial internal resistance
Kv	Motor velocity constant
MTOW	Maximum take-off weight
TOW	Take-off weight
OEW	Operational empty weight
PL	Payload
2D	Two dimensions
3D	Three dimensions
α	Angle of attack
Re	Reynolds number
V_{inf}	Airspeed

Introduction

Aim

The main objective of this study is to develop an aircraft designing tool. The use of multi-objective optimization algorithms, also known as genetic algorithms, will improve the final results allowing to achieve an optimal design of the wing planform. The study aims to integrate the MagAppConsolaV204, a self-developed software, with AVL and Xfoil in order to obtain the objective function that will be optimized by NSGA-II. Afterwards, final results will be evaluated and validated. The objective functions to be optimized will be the ones that Trencalòs Team considers appropriate for the participation in the Air Cargo Challenge 2015 competition, being the main goal the development of a working tool that allows the optimal design of an aircraft within the competition regulations.

Scope

The study will be divided into the following tasks:

- Introduction and state of the art.
- First contact with the designing tools for the code development: Xfoil, AVL, MagAppConsolaV204 and multi-objective optimization algorithms.
- Description of the ACC15 regulations in order to set the designing parameters.
- Objective function description.
- Implementation of the code in C++ programming language which integrates all previously mentioned software.
- Obtain, evaluate and validate the final results.

For the development of the study the following assumptions have been considered:

- The code will be written in C++ programming language.
- MagAppConsolaV204 program developed by Trencalòs Team will be considered as valid.
- The optimal planform of the wing will be of an aircraft exclusively designed for the participation in the Air Cargo Challenge 2015.
- The aerodynamic study with AVL and Xfoil will be considered reliable enough and no other similar programs will be needed.
- The wing is defined to be a trapezoid, so the number of variables that define its geometry will be limited to three: wing span, root chord and tip chord. Other parameters as the offset, dihedral or wing twist will not be considered.
- The study is based on the wing planform optimization, but the airfoil selection is not considered. NACA 4415 airfoil will be used.
- There will not be an experimental verification of the obtained results.
- All evaluated angles of attack will be integer values, with no decimal accuracy.

State of the Art

Trencalòs Team

Trencalòs Team is a group of students belonging to ETSEIAT engineering school at *Univeritat Politècnica de Catalunya – BarcelonaTech* in Terrassa, Barcelona. The main goal of the Team is to develop projects related with aeronautical science as a platform to give students a hands-on experience to complement their academic education. Trencalòs was born in 2006 to compete in the Air Cargo Challenge (ACC) international competition held in Lisbon the summer of 2007. Since that first experience, Trencalòs has kept his founding principles developing other projects such as three more participations in the ACC competition (2009, 2011, 2013), a long endurance solar sailplane (Solar Endeavour), a F5J plane and the electronic platform for an UAV. A brief description of the projects can be found in the web site of the team ***(1)***.

Moreover, since the end of 2013, Trencalòs Team organizes the student competition Paper Air Challenge at ETSEIAT – UPC Terrassa. The main goal of the competition is to design, build and fly a glider, entirely made of cardboard and paper. The competition is open to the public, yet linked to two subjects where students have the opportunity to apply the knowledge acquired in class.

Air Cargo Challenge

Air Cargo Challenge (ACC) is an aeronautical competition organized in Europe every two years. The competition was born in Portugal in 2003, organized by the APAE: Associação Portuguesa de Aeronáutica and primarily aimed to aerospace and aviation students. The main goal of the competition is to design and build a radio-controlled aircraft capable of flying with the highest payload possible, according to the regulations established by the organization. The score of each team is not only obtained by the performance during the flight, but also by the technical quality of the project evaluated through the Final Design Report, the drawings and an oral presentation.

Since 2007 the competition grew to an international level under the umbrella of EUROAVIA, the European Association of Aerospace Students, currently participating teams of universities from all around the world (China, Brazil, Egypt, etc.). The Air Cargo Challenge offers students the unique opportunity to develop a multidisciplinary and challenging project from its beginning to the finished product. By participating at ACC the teams can test their knowledge and, at the same time, get involved with a wide range of challenges which students will find in their future professional career: technical, interpersonal and financial challenges as well as strict deadlines.

Air Cargo Challenge 2015

From the beginnings of the Air Cargo Challenge, the main goal of the airplanes was to carry as much payload as possible, but without time considerations. For the 2015 edition, held in Stuttgart (Germany), a remarkable variation in the regulations slightly changes the main objectives; the aircraft has to be designed for a more realistic mission: carry as much payload as possible in a given time, meaning that the final score depends on the payload and the maximum speed reached by the aircraft. Described in the ACC15 Regulations ***(2)*** the aircraft must take-off in under 60 meters, fly as many 100 metre legs as possible within two minutes and land safely in the place previously defined by the organizing committee. The aircraft must comply with the following competition's regulations which include design restrictions such as limited motor power and aircraft dimensions.

In contrast to the previous editions where only successful take-off and landing were required, a distance task is added to the flight mission this time. This is done to account for the importance of transport efficiency in real life, as well as to continue the variation of the design goals and limitations between the editions of the competition.

All information about Air Cargo Challenge 2015 can be found in the current web site ***(3)***.

Justification and opportunity

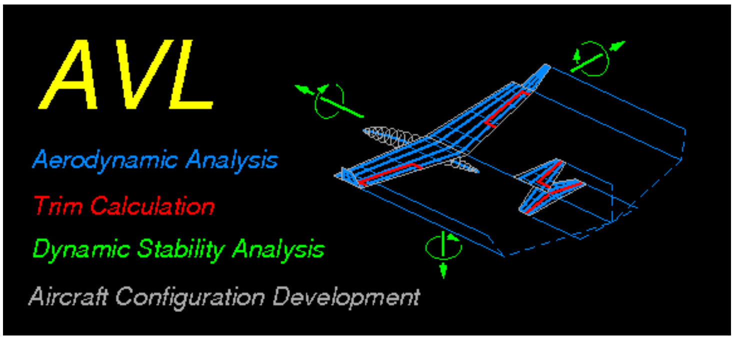
The developed program pretends to be a key to find the optimal planform of a wing of a UAV for a certain mission. In this case, it is desired to find the best solution that fits in the regulations of the 2015 edition of the international competition Air Cargo Challenge: carry as much payload as possible and reach the highest velocity as possible.

Currently, Trencalòs Team uses similar tools to design a small-scale aircraft, but the process is slow and an optimal solution is never reached due to the lack of capabilities and time. Therefore, the aim of this code is to automate the design process and be able to reach a better solution, becoming an essential designing tool for Trencalòs Team.

Description of the programs integrated in the code

The main tools that will be used for the development of this study are the MagAppConsolaV204 software, AVL and Xfoil aerodynamics programs and the multi-objective function optimization code NSGA-II.

AVL



To obtain the aerodynamic data of the wing **AVL** *(6)* software will be used. It is a program for the aerodynamic and flight-dynamic analysis of rigid aircraft of arbitrary configuration, based on the VLM (*vortex lattice method*) model for the lifting surfaces together with a slender-body model for fuselages and nacelles. The VLM is a numerical method used in fluid mechanics with which lifting surfaces of an aircraft can be modelled (the wing, horizontal stabilizer, etc.) using a discrete number of vortices to compute the lift or the induced drag, among other parameters. This is a simple analysis method, commonly used in the early stages of the design process of an airplane.

However, one of the weaknesses of this software is that it neglects the viscosity of the fluid (in this case, the air), treated as an ideal or potential flow. In aerodynamic terms this means that the following aspects are not calculated:

- Turbulence
- Detachment of the boundary layer
- Friction drag coefficient
- Pressure drag coefficient

Hence, VLM can be a very useful and effective as a first approach for calculating the aerodynamic coefficients of an airplane.

The document provided by the developer *(7)* has been essential for learning the correct functioning of the program.

XFOIL

As achieving a first approach of the design of an airplane is not the aim of the project, **Xfoil** *(6)* program will be used in order to provide more rigor and obtain more reliable results, including viscous analysis and being able to approach the boundary layer detachment.

Xfoil is an interactive program for the design and analysis of subsonic isolated airfoils. It consists of a collection of menu-driven routines which perform various useful functions such as:

- Viscous (or inviscid) analysis of an existing airfoil, allowing:
  - Forced or free transition

  - Transitional separation bubbles
  - Limited trailing edge separation
  - Lift and drag predictions just beyond maximum C_l
  - Karman-Tsien compressibility correction
  - Fixed or varying Reynolds and/or Mach numbers
- Airfoil design and redesign by interactive modification of surface speed distributions, in two methods:
  - Full-Inverse method, based on a complex-mapping formulation
  - Mixed-Inverse method, an extension of Xfoil's basic panel method
- Airfoil redesign by interactive modification of geometric parameters such as:
  - Maximum thickness and camber, highpoint position
  - Leading edge radius; trailing edge thickness
  - Camber line via geometry specification
  - Camber line via loading change specification
  - Flap deflection
  - Explicit contour geometry (via screen cursor)
- Blending of airfoils.
- Writing and reading of airfoil coordinates and aerodynamic coefficient files.
- Plotting of geometry, pressure distributions, and multiple data.

Hence, the incorporation of Xfoil into the code will allow to collect aerodynamics data based on the Reynolds number in order to enhance the results obtained with AVL and reach to a more reliable final solution.

The document provided by the developer *(7)* has been essential for learning the correct functioning of the program.

MagAppConsolaV204

The **MagAppConsolaV204** is a C++ in-house coded software developed by Trencalòs Team capable of calculating take-off, propulsive and flight performance of an aircraft given its electric engine parameters, propeller and aerodynamic characteristics. The program is the result of all the computational developments made since ACC'09. In order to use this program to evaluate the performance of certain airplane configuration in the design process of the ACC15, the code capabilities have been expanded to the computation of the ACC15 flight score achieved by each proposed alternative. To do so, a mathematical model for the turns in the competition mission has been included. At its current state, as described in *(8),* MagAppConsolaV204 is capable of:

- Calculating the Take-Off run needed for certain aircraft to take off.
- Calculating the MTOW for certain airplane and fixed runway length.
- Calculating the steady climb manoeuvre after take-off.

- Calculating the cruise stage of the airplane (with the trust requirements, the electric performance of the engine is evaluated) .
- Calculating the endurance and range of the airplane for a given battery pack.
- Calculating the time needed to perform a certain turn at certain G's.
- Calculating the score of the mission for a certain aircraft configuration.

Each of these capabilities is independent and can be performed individually or in a sequential procedure to get the final ACC15 competition score.

The data needed to perform the computations will be obtained from AVL aerodynamics program. It includes:

- An AVL file with aerodynamic coefficients at a fixed angle of attack and varying speeds to be used in the take-off run.
- An AVL file with aerodynamic coefficients for an angle of attack range to be used in the steady-climb and cruise stages, with MTOW.

The aerodynamic characteristics of the propeller and the engine and battery parameters are also required. Its calculation is out of the scope of this study, however, the data obtained by Trencalòs Team will be used:

- The electric parameters of the engine: Kv, I_0, R_0
- The aerodynamic characteristics of the propeller $C_T = f(J)$, $C_P = f(J)$
- The electric parameters of the battery pack: Capacity, discharge ratio, voltage, R_0bat

Some of the limitations of the code capabilities arise from the hypothesis in which the computations are based. These simplifying hypothesis include:

- The use of steady-state computations without acceleration (steady-climb, steady-cruise). This hypothesis is not applied in the take-off solver.
- The use of a constant voltage for the engine. As the battery capacity drains, the voltage drops, so the computations have been made using a lower voltage from the nominal value.
- The drag induced by the fuselage is neglected. Only the wing drag is used in the computations.
- The assumption that the rotation manoeuvre after take-off is instantaneous.

NSGA-II

"Multi-objective optimization (also known as multi-objective programming, vector optimization, multicriteria optimization, multiattribute optimization or Pareto optimization) is an area of multiple criteria decision making, that is concerned with mathematical optimization problems involving more than one objective function to be optimized simultaneously. Multi-objective optimization has been applied in many fields of science, including engineering, economics and logistics where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. Minimizing cost while maximizing comfort while buying a car, and maximizing performance whilst minimizing fuel consumption and emission of pollutants of a vehicle are examples of multi-objective optimization problems involving two and three objectives, respectively. In practical problems, there can be more than three objectives.

Product and process design can be largely improved using modern modelling, simulation and optimization techniques. The key question in optimal design is the measure of what is positive or desirable about a design. Before looking for optimal designs it is important to identify characteristics which contribute the most to the overall value of the design. An optimal design typically involves multiple criteria/objectives such as capital cost/investment, operating cost, profit, quality and/or recovery of the product, efficiency, process safety, operation time etc. Therefore, in practical applications, the performance of process and product design is often measured with respect to multiple objectives. These objectives typically are conflicting, i.e. achieving the optimal value for one objective requires some compromise on one or more of other objectives.

For example, in paper industry when designing a paper mill, one can seek to decrease the amount of capital invested in a paper mill and enhance the quality of paper simultaneously. If the design of a paper mill is defined by large storage volumes and paper quality is defined by quality parameters, then the problem of optimal design of a paper mill can include objectives such as: i) minimization of expected variation of those quality parameter from their nominal values, ii) minimization of expected time of breaks and iii) minimization of investment cost of storage volumes. Here, maximum volume of towers are design variables. This example of optimal design of a paper mill is a simplification of the model used in." ***(9)***

Program requirements based on Air Cargo Challenge 2015

The design of the aircraft is totally dependant from the regulations of the competition imposed by the organization committee. Every edition of the Air Cargo Challenge the restrictions have slight changes which require a whole new aircraft concept:

- Air Cargo Challenge 2007:
    - Maximum wing span limitation
- Air Cargo Challenge 2009:
    - Maximum wing surface limitation
- Air Cargo Challenge 2011:
    - Maximum OEW limitation
- Air Cargo Challenge 2013:
    - Transportation box dimensions limitation

ACC15 Regulations

Air Cargo Challenge 2015, organized by Euroavia Stuttgart as well as Akamodell Stuttgart, clearly differs from previous editions, where only successful take-off and landing were required: a distance task is added to the flight mission this time. This is the key point of the 2015 edition of the competition. The main requirements are explained in the 2015 Regulations sheet ***(2,3)***, which includes the following points:

- "The team should design and build a radio controlled aircraft with limited outer dimensions: **the assembled plane shall fit in a 2.5 m x 2.5 m square** while standing on its landing gear."
- "The aircraft should be able to **take-off within 60 metres with the maximum payload possible."**
- "The aircraft should be able to cover a maximum distance in a defined time. During this time **as many legs as possible shall be flown on a 100 meters course**. Only fully flown legs by the end of the countdown will count."

Those requirements are the main points that will finally determine the aircraft design, so a more detailed analysis will be done. However, other requirements have also to be taken into account:

- "The aircraft may be of any configuration except rotary wing or lighter- than-air (for example, helicopters, autogyros, dirigibles, balloons are excluded)."
- "No form of externally assisted take-off is allowed. All energy for take-off must come from the on-board propulsion battery pack(s). The only means of aircraft propulsion is the prescribed electric motor."
- "The motor must be an unmodified AXI Gold 2826/10. The aircraft must be driven by a single motor."
- "The only Propeller allowed is an unmodified APC 13x7 inches Sport (manufacturer Product Code LP 13070)."
- "All Lithium based batteries (LiPo, LiFe, LiIon) can be used. The teams can use up to 3 cells in series. The product of max. continuous discharge rate times the capacity has to be at least 45A."
- "The transportation box is limited in size and must not exceed 1100 x 500 x 400 mm^3."

The competition score given to the team is based on the payload carried and the number of flown legs in one flight. In order for a team to participate in the flight competition, it must fulfil all the requirements of the competition and must have previously tested the aircraft.

The flight competition consists of at least 3 scoring runs if weather conditions permit in which the teams will try to carry the maximum possible weight and fly a maximum number of legs in a 100 m course (Figure 1).

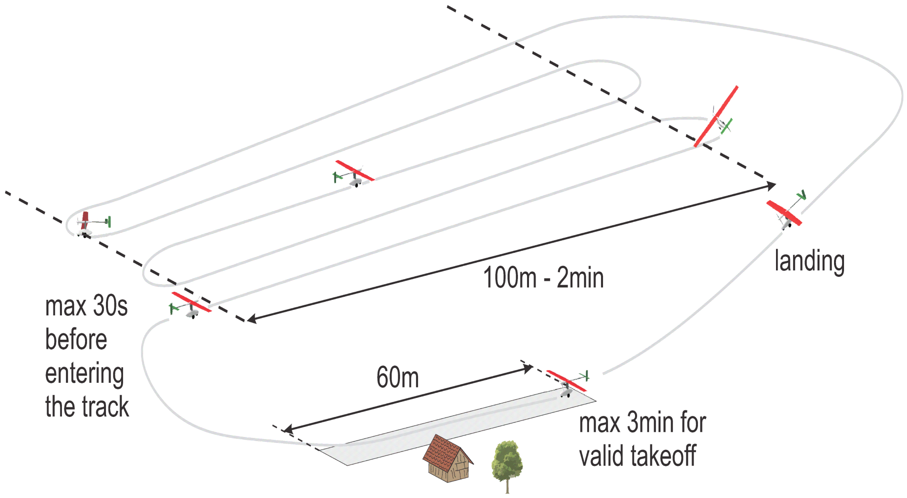


Figure 1. Graphical description of the flight pattern

The final score is determined using equation [1]:

$$\textbf{Flight Competition Score} = (PL[kg] \cdot 2) \cdot (\text{Flown Legs} + a) \cdot b \qquad [\,1\,]$$

Where:

- a = 2 for a valid start + non-valid landing
- a = 3 for a valid start + valid landing
- b = 1 for a valid flight without crash
- b = 0 for airplane losing parts or crashes or invalid start

Main requirements analysis

In this section the main requirements set in the regulations sheet of the Air Cargo Challenge 2015 will be deeply analysed, in order to define the main variable design parameters. The requirements to be analysed are:

- The limited outer dimensions of the assembled aircraft.
- Take-off performance and flight envelope characterization.
- Flying performance.

Outer dimensions limitation

The geometry of the airplane has always been the parameter to be limited and/or regulated. In this case, the aircraft not only has to fit into the transportation box of 1100x500x400 mm but also into a 2.5 m x 2.5 m square, completely assembled and while standing on its landing gear.

One of the possible aircraft configurations is the following, shown in Figure 2:

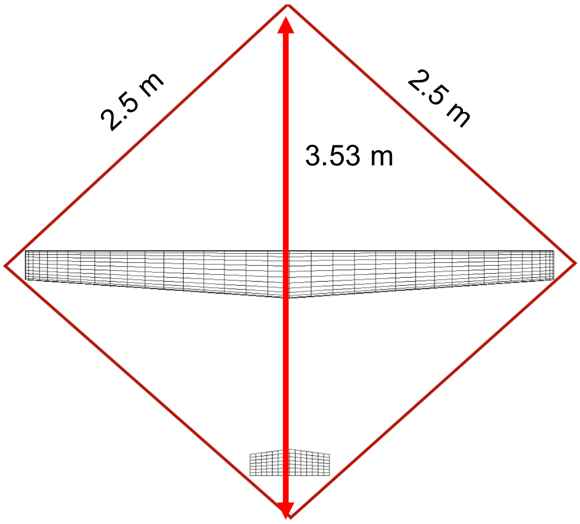


Figure 2. Possible aircraft configuration that fit into the 2.5x2.5m square

This configuration will provide the upper limits of some of the wing geometry design variables:

- Wing Span
- Tip Chord

In order to ensure that the wing always fits into the imposed square, a relation between both parameters has been calculated using [2]:

$$Wing\ Span = L_{max} - c_{tip} \cdot \tan 45^{\circ} \qquad [\,2\,]$$

Some of the possible values are shown in the following table (Table 1):

Tip Chord (mm)	Maximum Wing Span (mm)
100	3435,5
125	3410,5
150	3385,5
175	3360,5
200	3335,5
225	3310,5
250	3285,5

Table 1. Relation between maximum values of the tip chord and wing span

Otherwise, the last wing geometry design variable is the root chord, whose upper limit is restricted by the transportation box dimensions (Figure 3): 500 mm of maximum root chord. Defining a minimum value is not critical, so it will be set at 300 mm.

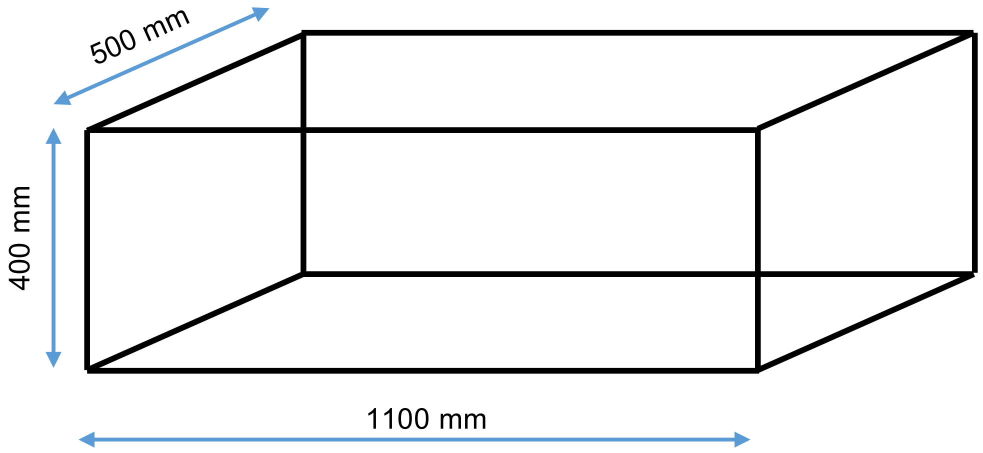


Figure 3. Transportation box dimensions

It is also vital to ensure that the whole wing will fit inside the transportation box. To do so, the maximum wing span must be divided into sections with maximum length of 1100 mm (Figure 4):

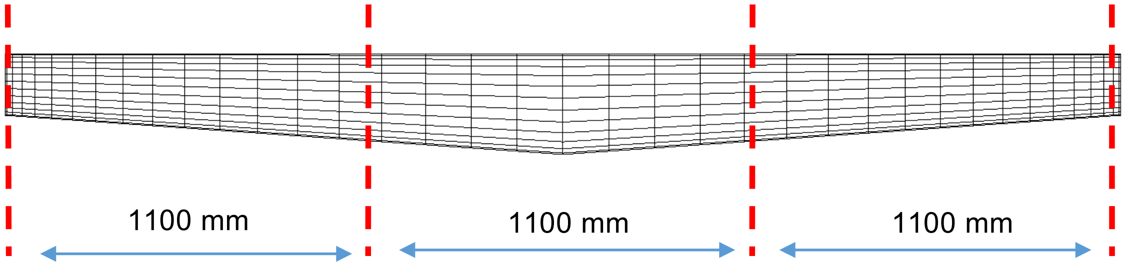


Figure 4. Maximum wing span divided into sections

Although the maximum wing span is grater than 3500mm for a tip chord smaller than 250mm, the upper limit is imposed by the transportation box and not by the 2.5x2.5m square. On the other hand, there is no lower limit for the wing span value, so the following is assumed: the minimum value for the wing span will be small enough to fit into the transportation box in two pieces, taking a value of 2000mm. If the final results showed that with smaller wings the score is increased, this assumption would be considered again.

Regarding the maximum tip chord, its relation with the maximum wing span [2] has been used to set a maximum value, always leaving a safety factor due to possible constructive imprecisions. The minimum value of the tip chord has been set at 100mm, assuming that smaller values would hinder the construction and penalize the final result

So to conclude, Table 2 summarizes the obtained results:

	Maximum possible value	**Minimum value**
Wing Span	3300mm	2000mm
Root Chord	500mm	300mm
Tip Chord	200mm	100mm

Table 2. Maximum and minimum values of tip chord and wing span

Take-off

The aircraft has to take off within 60m, otherwise the flight attempt is invalid. Since the beginning of the Air Cargo Challenge this requirement has always been maintained.

The MTOW is one of the parameters that characterize the design of an aircraft; so maximizing it while minimizing the OEW, a higher payload can be carried and a better competition score can be obtained. However, although in larger wings the OEW might be bigger than for smaller ones, this value will be assumed as constant. The reasons for this assumption are the following:

- The value of the OEW is very small (2.2 kg). Therefore, getting this weight reduced is a difficult and sometimes impossible challenge.
- If the wing was larger, the plane would stand out for its MTOW capacity and not for its maximum speed, so the structure weight may be reduced (smaller load factor during flight).
- If the wing was small, the plane would stand out for its maximum speed and the load factor during flight would be higher. Thus, the structure would be more consistent and, therefore, heavier.
- Considering that the wing is not a unique piece of solid material, but a single beam with the corresponding ribs and stringers, the density of the wing will not be constant: for bigger wings, lower density; for smaller wings, higher density.

So if the operational empty weight is considered to be a constant factor, the Payload is mainly defined by two variables: the wing geometry and the take-off distance. So the 60m of take-off distance imposed by the regulations define one of the design variables which is used in the MAgAppConsolaV204 program, where take-off is simulated.

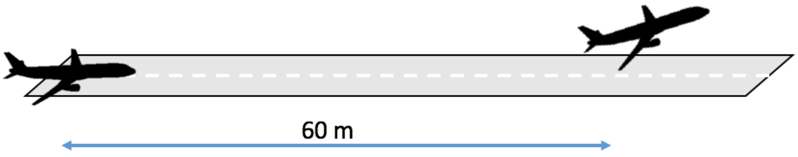


Figure 5. Take-off distance

Flight performance

This point is one of the keys of the design of the ACC15, so the plane must fly fast and have a good manoeuvrability. This change in the rules might cause that the concept of aircraft used up to now may not be the best solution, and some questions come across:

- Is it better a light and fast aircraft than slow and heavy one?
- Should be prioritized a high lift coefficient, a high aerodynamic efficiency or a low drag coefficient?
- What kind of airfoil should be used?
- Which is the best plan form for the wing? Are big aircrafts still better than smaller ones?

The answer to these questions can be obtained by the way that Trencalòs Team has always used, trial and error, which is slow and not always totally concluding. However, with the development of this project, a fast, reliable and very much concluding way to find an optimum design of the aircraft for this specific mission will be created.

So the next point explains the process that has been followed to create the integrated code for calculating the optimal plan form of a wing within the Air Cargo Challenge 2015 competition rules and regulations.

Program development

General description

The aim of the study is to develop a C++ code that integrates existing aerodynamic software with the goal of achieving an objective function to be optimized with a genetic algorithms. The aerodynamic programs to be integrated are:

- Xfoil
- AVL
- MagAppConsolaV204

The program is divided into two differentiated parts, which are complementary and essential:

- **2D aerodynamic database creation**. Xfoil program has been used in order to create a database of aerodynamic properties of the desired NACA airfoil, in a range of Reynolds number.
- **3D analysis**. This part of the program does not work if the 2D aerodynamic database has not been previously created. The goal of this code is to analyse a proposed 3D wing with AVL program in order to obtain the corresponding aerodynamic properties. The calculated 3D data is necessary to simulate the take-off, climb and flight performance of the plane with MagAppConsolaV204 and

obtain the score of the Air Cargo Challenge 2015 competition, the objective function.

- **Plan form optimization**. Finally, the use of the genetic algorithm NSGA-II allows the maximization of the objective function. The input variables into the optimizer are the tip chord, the root chord and the wing span of the aircraft. The genetic algorithm proposes different values of the mentioned variables in order to maximize the objective function, which is traduced into a wing planform optimization. The process that will be followed to do is:
    - The open-source genetic algorithm has to be executed into the main folder of the project.
    - Some inputs are required, which are:
        - **Enter the population size (a multiple of 4, because it is the number of parents): 12**. This is the amount of cases to be analysed in each generation, which shall be bigger than the number of real variables. For a fast optimization, this parameter should be small. For our case, this value will be 12.
        - **Enter the number of generations: 3, 6, 12, 24**. In each generation, all population is created and the function objective is calculated for each case. The created population in each generation is not random; as NSGA-II is an evolutionary code, every generation is better than the previous one. If more generations are analysed, the final results will be better.
        - **Enter the number of objectives: 1**. In this case, although for obtaining the maximum score in the competition both the MTOW and the maximum velocity of the aircraft have to be maximized (2 objective functions), only the score itself is considered, so the number of objective functions are minimized and the process is simpler.
        - **Enter the number of constraints: 0**. This value is set to 0.
        - **Enter the number of real variables: 3**. The variables to this problem are the ones that define the wing geometry (wing span, the tip chord and the root chord). However, the code can easily be expanded and the geometry of the wing can be defined by as much variables as desired.
        - **Enter the upper and lower limits of real variables**. It is necessary to define the minimum and maximum values that can be proposed by the genetic algorithm. The values are the ones defined in Table 2.

A general description of the whole program is described in Figure 6:

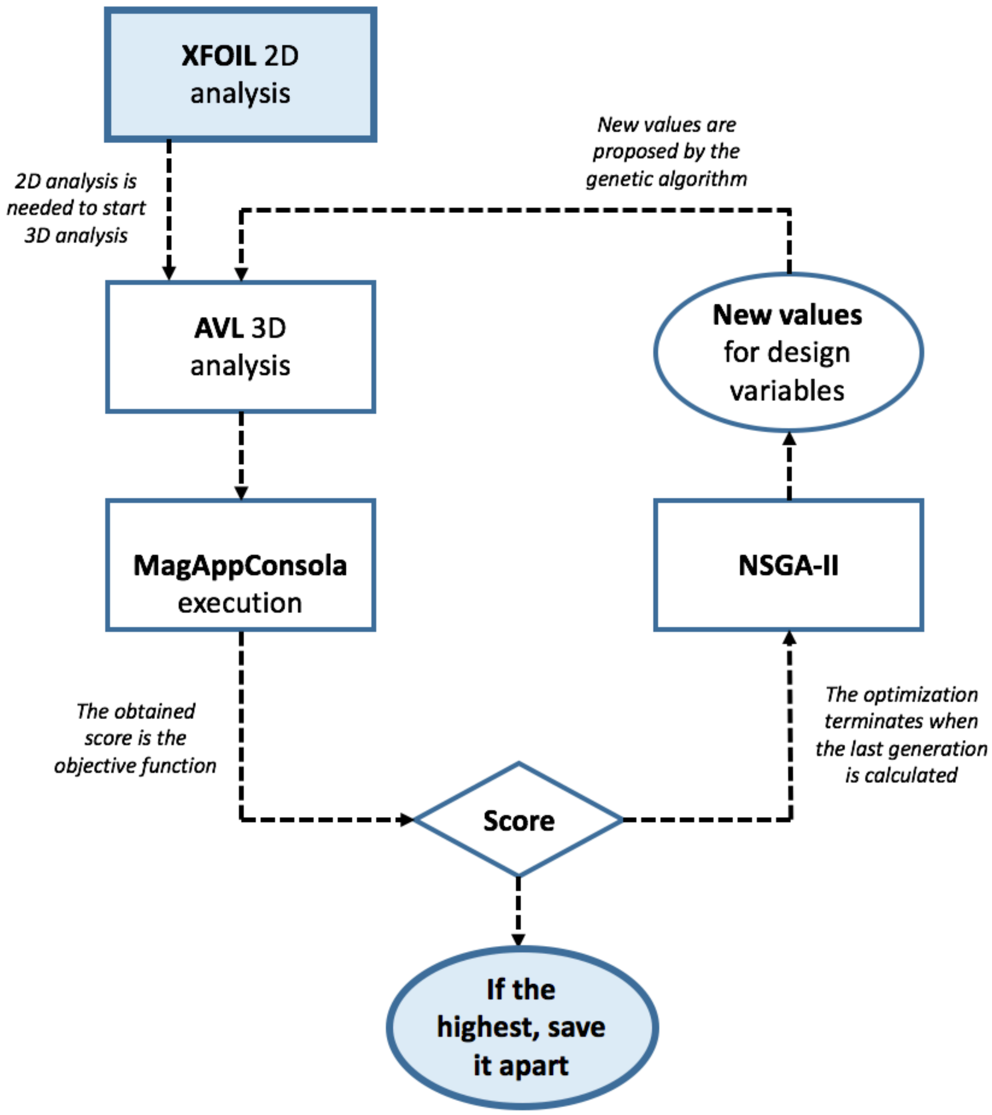


Figure 6. Description of the general code

2D analysis

The first step in the objective function calculation is to have a data base of aerodynamic characteristics of the chosen airfoil in function of the Reynolds number, calculated with XFOIL; so a 2D code has been developed in order to achieve this goal. The software creates text files which contain aerodynamic properties of the airfoil for certain Reynolds numbers, such as the lift coefficient (Figure 7) or parasite drag coefficients (Figure 8). To do so, a first approach to the maximum and minimum values of the Reynolds number has to be calculated using equation [3]:

$$\mathrm{Re} = \frac{\rho v_s D}{\mu} \qquad [\,3\,]$$

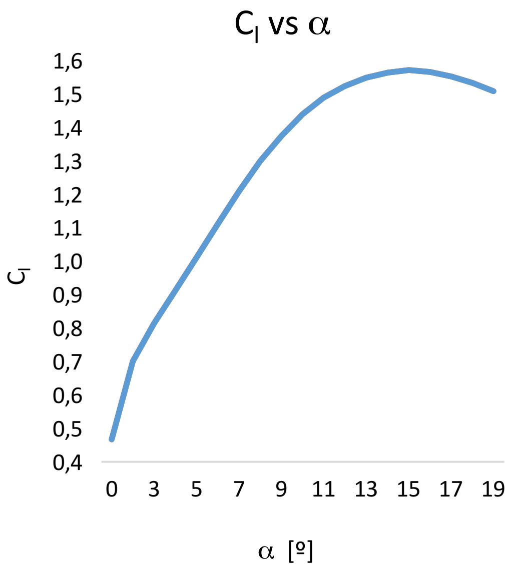


Figure 7. Lift coefficient versus the angle of attack of the NACA 4415 airfoil

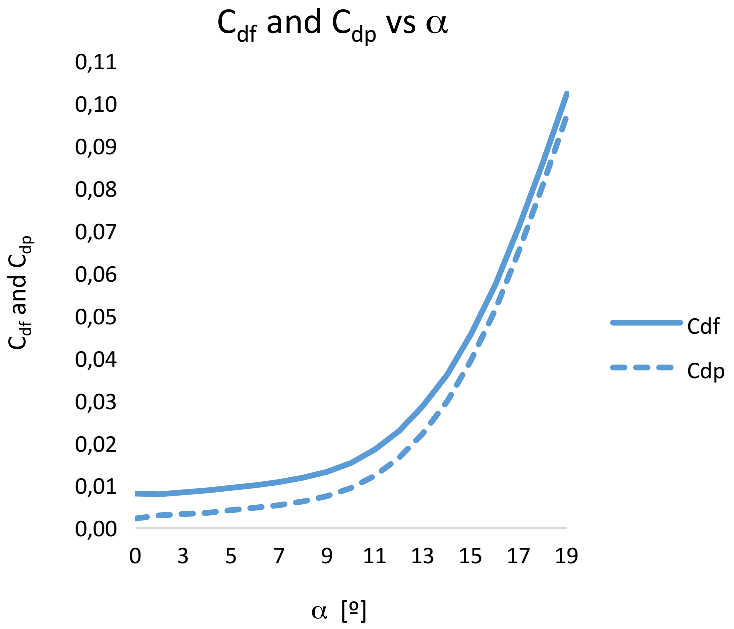


Figure 8. Form and pressure friction coefficients versus the angle of attack of the NACA 4415

Maximum and minimum values of the Reynolds number will be inputs for the user. In the other hand, the increase value of the Reynolds number for each iteration will be fixed and the user will not be able to change it. A small increase has been chosen so the results can be reliable enough and the interpolation will be performed between similar values. All created data will be saved into text files named with the corresponding value of the Reynolds number, kept in a specific folder.

The calculation process is the following, also explained in Figure 9:

- **Initial data**. Before executing the 2D program, the user must decide which airfoil will be used. All NACA airfoils family is available. It is also necessary to introduce the minimum and the maximum angle of attack of the airfoil to be analysed. It is desirable to choose a big range, so that no aerodynamic data is ignored.
- **User input.** Desired maximum and minimum values of the Reynolds number must be introduced by the user. These values will set the beginning and the end of the loop where Xfoil will calculate the corresponding aerodynamic data. For example:
    - **Re_{min} = 10000**
    - **Re_{max} = 2000000**

  With these inputs, 200 different aerodynamic polars will be calculated, saved into different text files and named with the corresponding Reynolds number.
- **Xfoil**. For each Reynolds number the software will calculate and save all aerodynamic parameters versus the angle of attack, in the specified range.
- **Final calculations**. Once the Reynolds number loop for Xfoil calculations has ended and all polar files are correctly saved and placed, another loop with the same lower and upper limits starts. In this case, each file is evaluated in order to find the maximum value of the lift coefficient, as well as the pressure and friction drag coefficients versus the angle of attack. The lift coefficient and the drag coefficients values will be saved into different files, so that at the end of the program the following data will be available:
    - **Data file**. Named with the corresponding Reynolds number (i.e. 240000.txt), it will contain all aerodynamic coefficients of the airfoil.
    - **Maximum lift coefficient file**. Named with the corresponding Reynolds number plus a differential character (i.e. 240000_clmax.txt), it will contain the maximum value of the lift coefficient of the airfoil in the evaluated Reynolds number.
    - **Pressure and friction drag coefficients file**. Named with the corresponding Reynolds number plus a differential character (i.e. 240000_cd.txt), it will contain both pressure and friction drag coefficients versus the angle of attack of the airfoil in the evaluated Reynolds number.

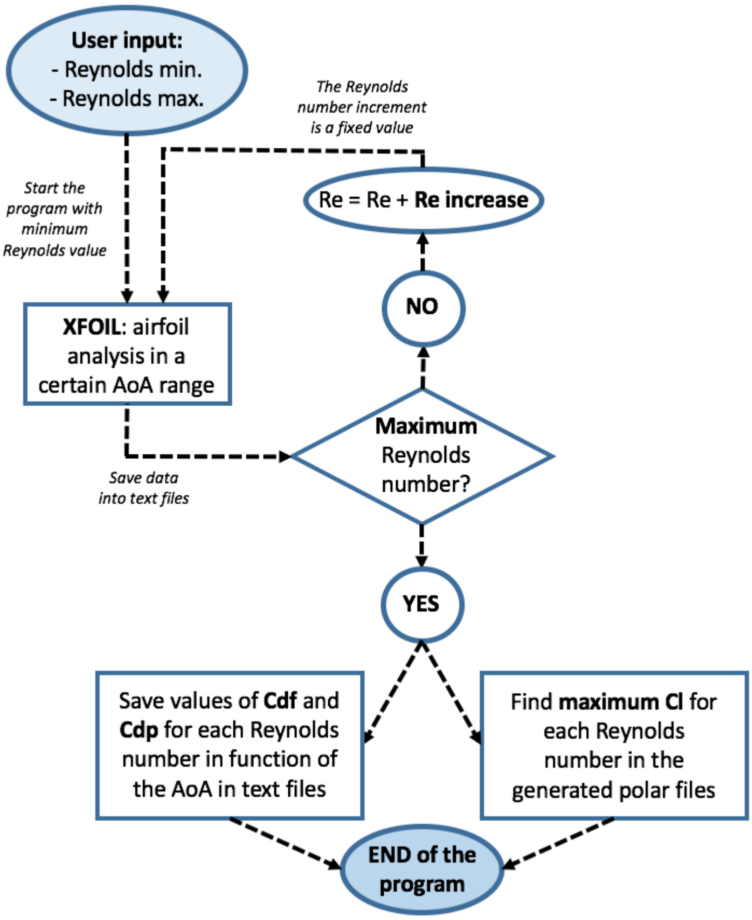


Figure 9. Description of the 2D code

3D analysis

The main structure of the program is the 3D analysis, which is carried out with AVL and MagAppConsolaV204. As vortex lattice method does not calculate the boundary layer detachment, XFOIL analysis is needed. So it is essential for the correct functioning of the program having previously executed the 2D analysis and have obtained the aerodynamic properties of the airfoil, always inside the proper Reynolds number range. The calculation process is the following:

- **Initial data**. The value of the air density is a parameter that must be entered by the user, as well as the airfoil that will be used to do the analysis. The possible airfoils to be analysed are the NACA family ones and the selected airfoil must be the same as the analysed in the 2D analysis, otherwise it will not work properly. Another important parameter to be defined before the program starts is the TOW of the airplane. This parameter is only an initial estimation, as it will be automatically iterated in order to approximate it to the MTOW of the proposed aircraft.
- **Geometry file**. The geometry of the wing to be analysed is described in a text file with the AVL required format. So every time that the optimizer proposes

values of the tip chord, root chord and wing span a new geometry file is created, replacing the old one.

- **Angle of maximum lift coefficient**. This part of the program is probably the most important one. AVL is based on Vortex Latice Method, so the boundary layer detachment is not contemplated and the maximum angle of attack can not be calculated. The following process has been considered in order to solve this problem:

    - Initially AVL is executed and the lift coefficient for all desired angles of attack is calculated. All lift coefficients are used to calculate the velocity of the aircraft with the TOW, for each flight condition, using equation [4]

$$V_{inf} = \sqrt{\frac{2 \cdot M \cdot g}{S \cdot C_L \cdot rho}} \qquad [\,4\,]$$

    - Then, a loop is started with the angle of attack at its minimum value as initial parameter. For each angle of attack the wing is divided into equal length sections, c(y), and the distribution of the lift coefficient is calculated with AVL, C_L(y) (Figure 10):

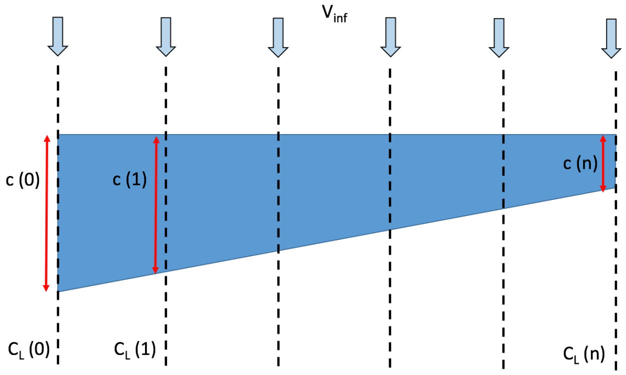


Figure 10. Chord c(y) and local lift coefficient C_L(y) distribution

    - For each section of the wing, c(y), and using the previously calculated airspeed, the corresponding Reynolds number is calculated using equation [3].
    - Every local lift coefficient of the wing for the current angle of attack is compared with the corresponding value of maximum lift coefficient in the 2D analysis database. To do so, an interpolation between the maximum lift coefficient of the most similar values of the Reynolds number in the 2D database is done and it is compared with the current 3D local lift coefficient. When the maximum lift coefficient of the 2D database is lower than the 3D local lift coefficient, the wing is considered to have achieved its maximum lift coefficient, as well as its maximum angle of attack.
      A more expanded explanation is presented below:

In order to compare both lift coefficients, the corresponding aerodynamic properties of the airfoil calculated by Xfoil (2D analysis) of the most similar Reynolds numbers are used:

- If the calculated Reynolds number is 55329, then the interpolated values of the aerodynamic data will be the corresponding to: Reynolds=50000 and Reynolds=60000 (Figure 11 and Figure 12).

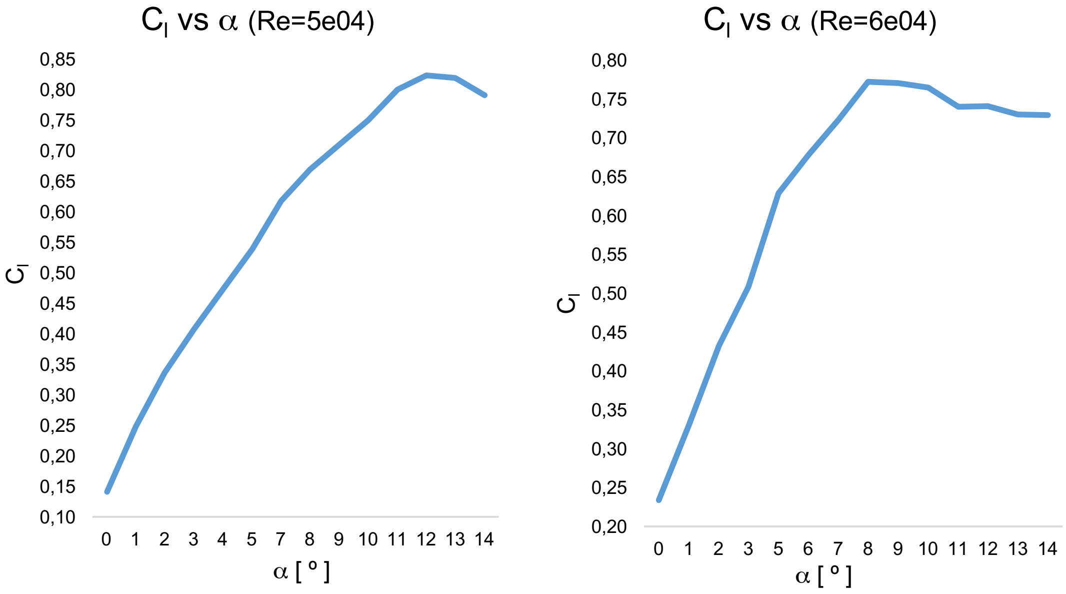


Figure 11. Lift coefficient vs the angle of attack of the NACA 4415 airfoil

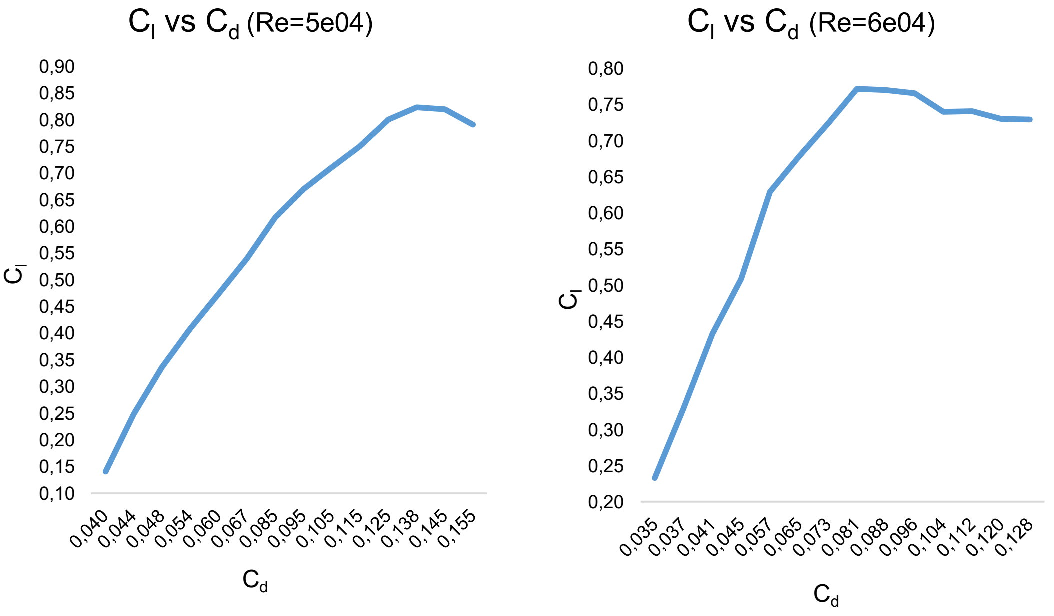


Figure 12. Lift coefficient vs drag coefficient of the NACA 4415 airfoil

An interpolation between both Reynolds needs to be done. Then, the local lift coefficient for the current angle of attack, calculated by AVL, will be compared with the maximum value of the polar calculated by Xfoil. The comparison is exposed below (Figure 13):

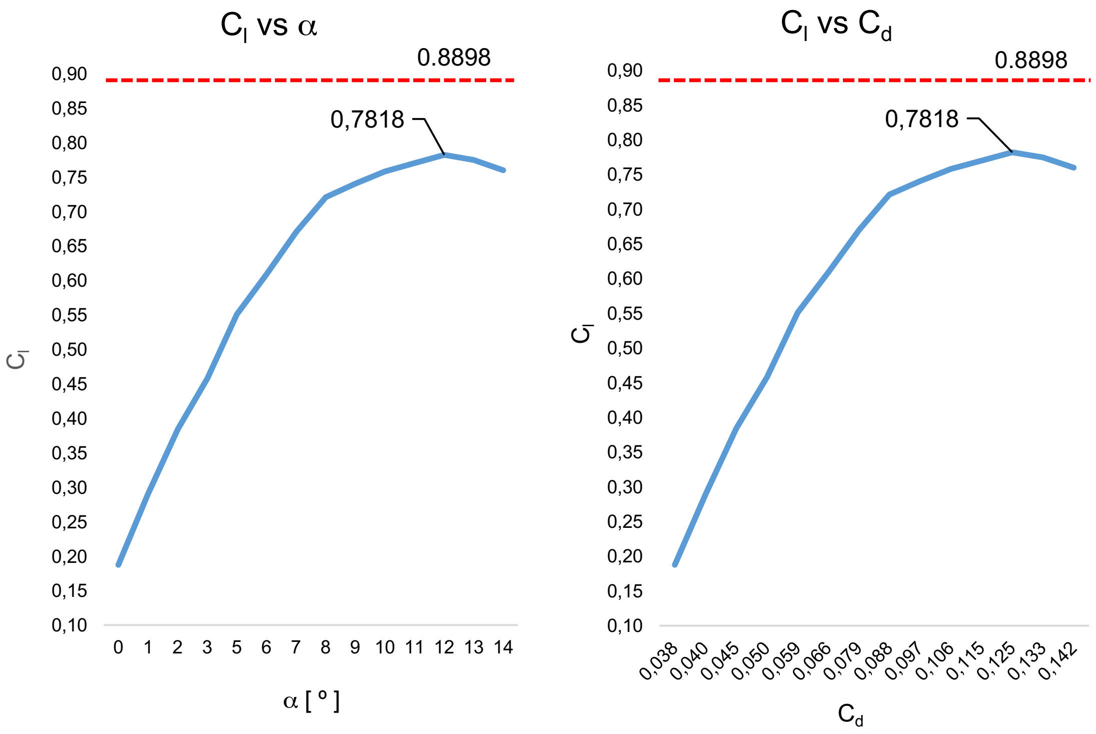


Figure 13. Aerodynamic characteristics of the airfoil NACA 4415 vs the required local C_l of the wing

In this case the required local lift coefficient, calculated by AVL ($C_{L\text{-}3D}(y) = 0.8898$), can not be interpolated with the polar given by Xfoil (2D analysis), because its value is bigger than the maximum C_l of the polar graph ($C_{lmax\text{-}2D} = 0.7817$). This means that this section of the wing has reached its maximum angle of attack before stall.

Although AVL calculates the global lift coefficient of the wing, 3D effects like wingtip vortices are not considered. However, this approach from 2D to 3D coefficients is considered to be good enough for this study.

So, for the maximum angle of attack calculation the following assumption has been considered: if only one section of the wing enters into stall, the wing will have reached its maximum angle of attack. This maximum angle of attack will be the upper limit for AVL lift coefficient calculation. This might be a conservative assumption, as only the lineal part of the C_L-α curve of the real flow is considered. However, it turns to be reliable enough for calculating the 3D maximum lift coefficient with AVL (potential flow), as shown in Figure 14:

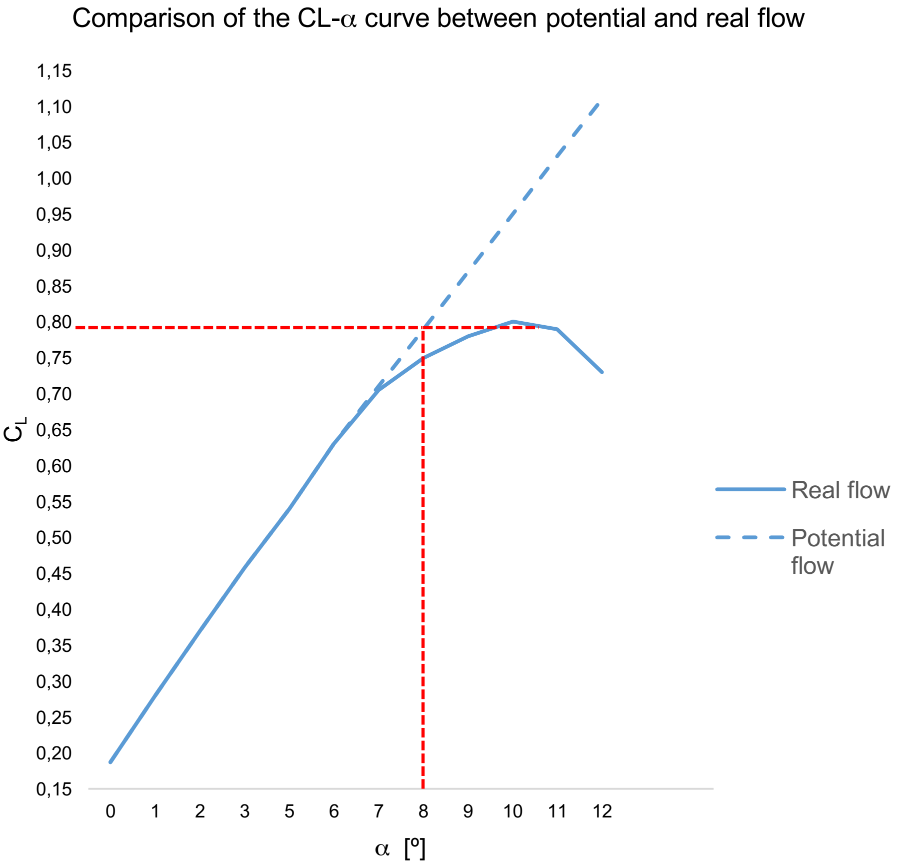


Figure 14. Comparison of CL-alpha curves between potential flow (AVL) and real flow

The red line indicates the point where at least one section of the wing has entered into stall condition. This point will be considered to be the maximum angle of attack of the wing for all aerodynamic coefficients calculation with AVL.

- **Parasite drag coefficients**. As AVL calculates only the induced drag of the wing, additional data is needed from Xfoil, where viscosity is considered. So for each wing section, the corresponding Reynolds number is used to obtain the friction and the pressure drag coefficients from the 2D database (C_{df} and C_{dp}), for the current angle of attack. Finally, once all sections of the wing have been calculated, the weighted median is calculated in order to find global drag coefficients C_{Df} and C_{Dp}. This is just a simplification, as a 2D coefficient is applied to a three dimensional wing, and 3D effects are not considered.
- **MTOW and competition score**. With all aerodynamic data needed to run MagAppConsolaV204, the MTOW and the competition score can be calculated. However, before analysing the final result, the MTOW has to be compared with the initial estimation of the aircraft mass, which turns to be [5]:

$$TOW = OEW + PL \qquad [5]$$

If the initial estimation of the TOW is smaller than the 95% of the MTOW the whole process is repeated using the following value [6]:

$$TOW_{new} = \frac{TOW_{old} + MTOW}{2} \qquad [6]$$

In the other hand, if:

$$0.95 \cdot MTOW < TOW_{new} < MTOW$$

the program ends and the obtained score, as well as the TOW is stored in a text file.

The whole 3D program is explained and summarized in the Figure 15:

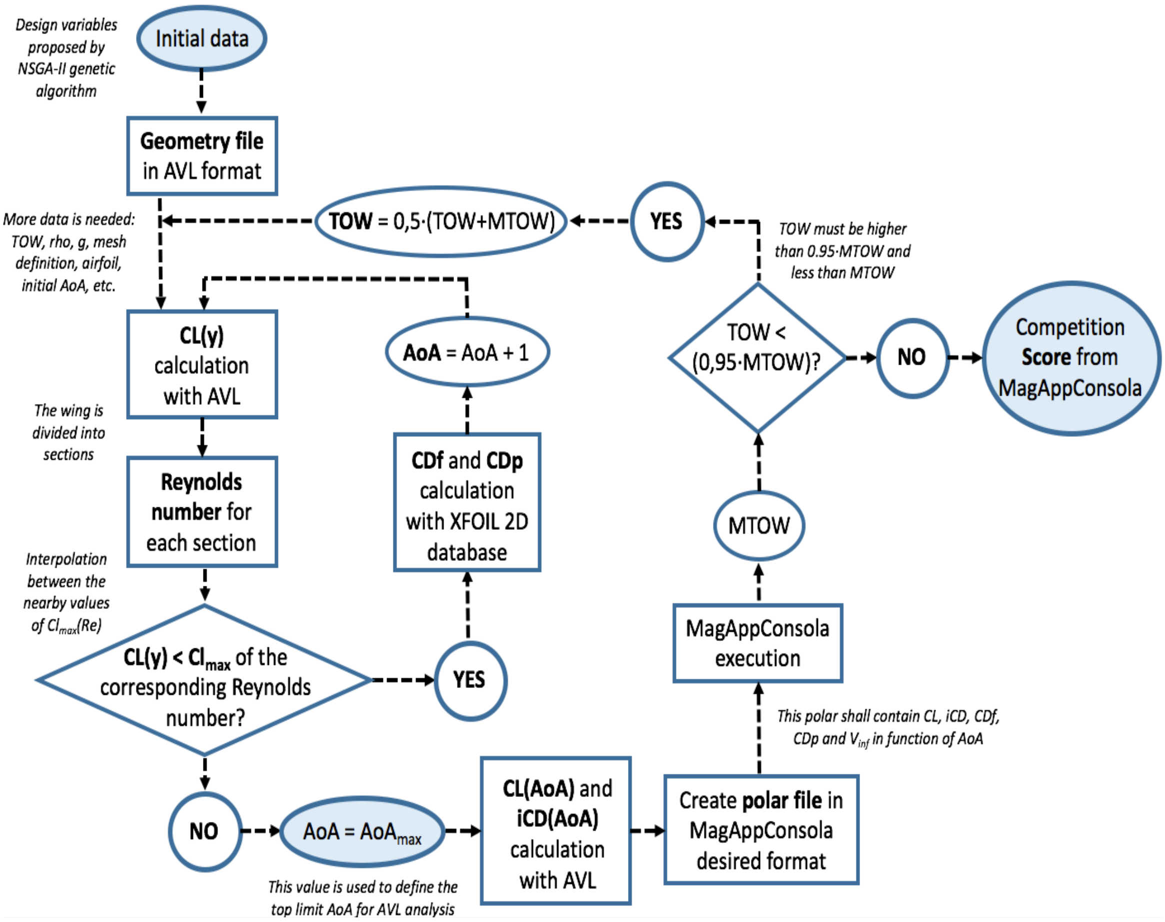


Figure 15. Description of the 3D code and the optimization process

Results evaluation and validation

Once the program running effectively, different kinds of analysis have been performed. The more generations that the optimization code creates, the more accurate the results will be, but also more time is needed to calculate them. So a progressively increase of the number of generations has been done, always maintaining the other parameters (the population, the upper and the lower limits of the variables, etc.).

The optimization process comprises the following steps:

- **3 result families**. This will be the first optimization, so it must be fast although the final are not concluding enough.
- **6 result families**. Double the number of generations will allow to obtain more conclusive results without sacrificing much time.
- **12 result families**. Four times the initial number of cases to be studied. With this number of cases, the trend of the value of the geometry variables in order to maximize the objective function will be clear and concluding.
- **24 result families**. Final study. With this analysis a mesh refinement will be done in order to obtain definitive results.

It is important to note that the genetic algorithm minimizes the objective function, which is not our intention. As we want to maximize the score of the competition, the objective function has been slightly modified in order to satisfy our demand:

$$\boldsymbol{Objective\ function} = \mathbf{1000} - \boldsymbol{score} \qquad [\,7\,]$$

Assuming that the competition score will never exceed 1000 points so the objective function will never be negative, the higher the score is, the lower the value of the objective function will be.

Five main plots have been extracted from each generations case:

- Objective Function [7] versus the generated cases
- Competition score versus the generated cases
- Wing span versus the generated cases
- Root chord versus the generated cases
- Tip chord versus the generated cases

Although the objective function of this study is the obtained score of the Air Cargo Challenge 2015 competition, the real objective is the wing geometry that allows this score. So for the final results obtained with the 24 generations analysis, a relation between the geometry variables and the obtained score has been plotted, so a more concluding study can be performed.

The following sections show the obtained results:

3 Generations Optimization

With Figure 16 and Figure 17 it is intended to show the optimization process of the objective function and the competition score, in a 3 generation analysis. Each generated case is a combination three values of the design variables (wing span, root chord and tip chord) which define the wing geometry:

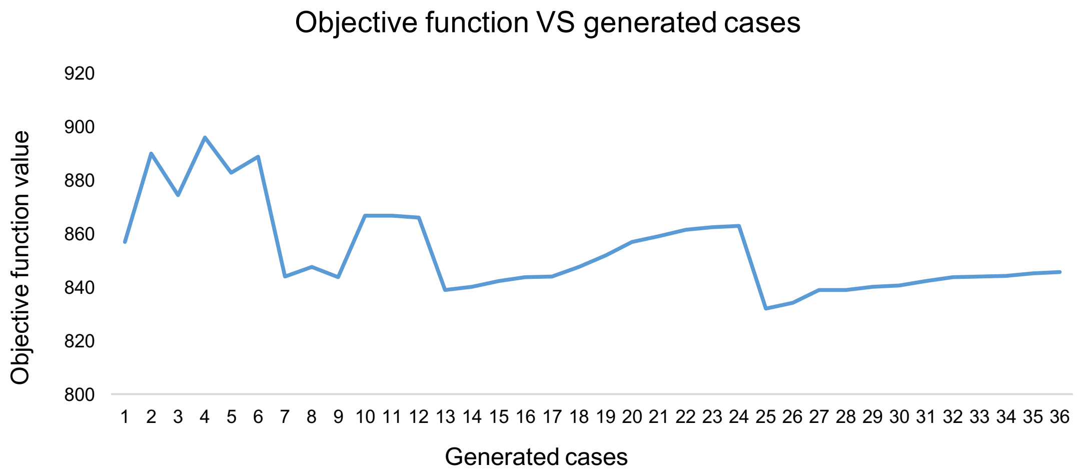


Figure 16. Minimization evolution of the Objective function in a 3 generation analysis

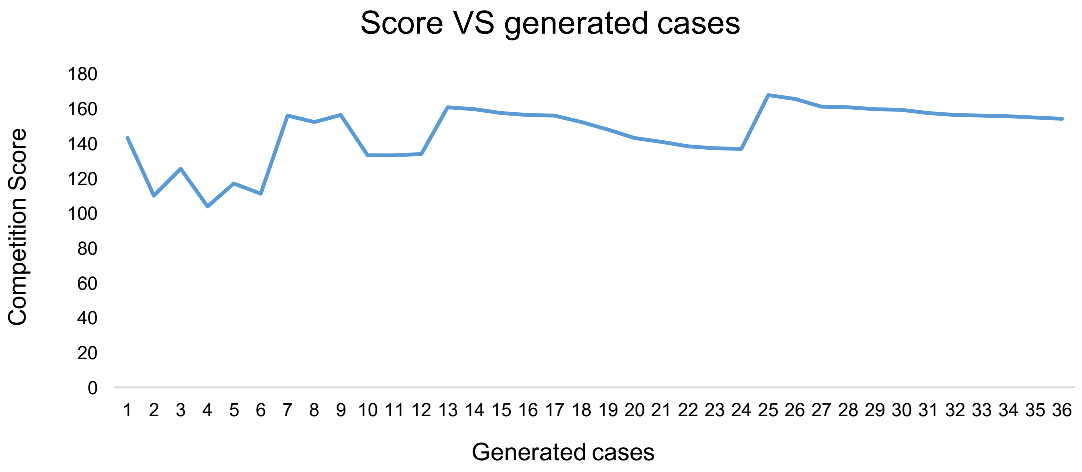


Figure 17. Maximization evolution of the competition score in a 3 generation analysis

As expected, the tendency of the objective function is to minimize its value in each generation analysis, whereas the tendency of the competition score is to maximize it. In the first generation the proposed cases follow no particular pattern, but serve to determine the beginning of the evolutionary trend.

Figure 18 shows the relation between the geometry of the wing and the generated cases:

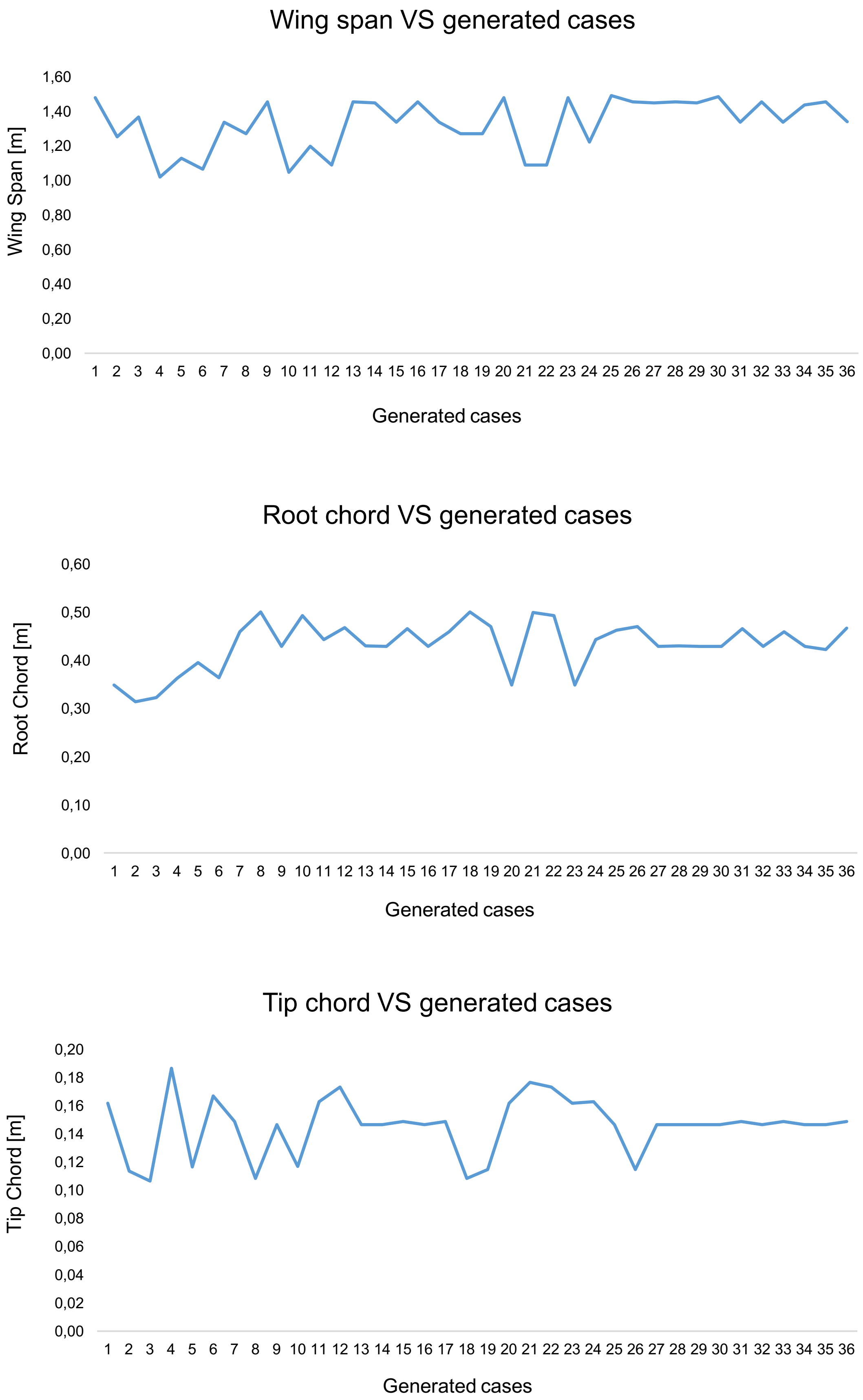


Figure 18. Evolution of the geometry of the wing in a 3 generation analysis

These graphs seem to show random geometry values without any clear trend, probably because the few analysed generations. So a first conclusion can not be extracted, because with a small number of analysed wings future results can not be precisely predicted.

The maximum value of the competition score (equivalent to the minimum value of the objective function) with the corresponding wing geometry that has been obtained in the 3 generations optimization process is (Table 3):

Score	Wing Span [m]	Root Chord [m]	Tip Chord [m]
167,93	2,98	0,46	0,15

Table 3. Best score and wing geometry in the 3 generations optimization process

Pictures of the optimum wing planform in the 3 generation optimization process are shown below (Figure 19 and Figure 20):

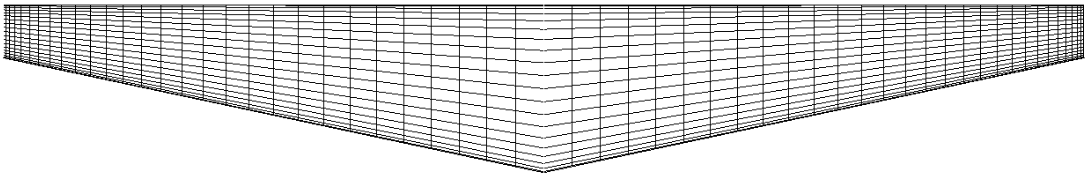


Figure 19. Optimum wing planform obtained from the 3 generations optimization process

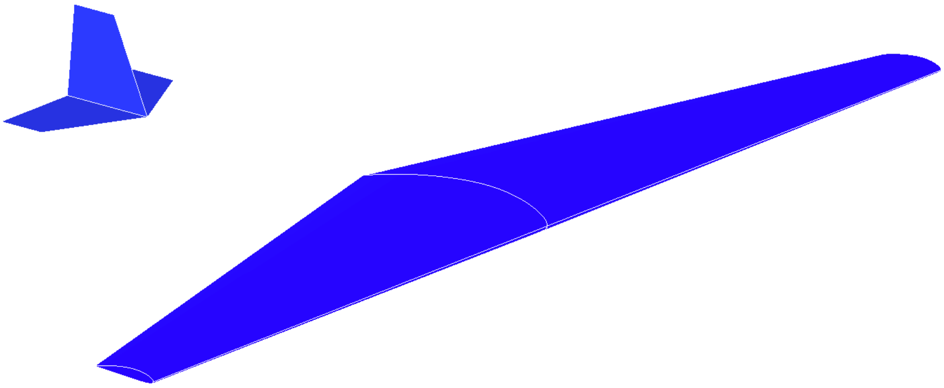


Figure 20. Conceptual design of the aircraft obtained from the 3 generations optimization process

6 Generations Optimization

With Figure 21 and Figure 22 it is intended to show the optimization process of the objective function and the competition score, in a 6 generation analysis. Each generated case is a combination three values of the design variables (wing span, root chord and tip chord) which define the wing geometry.

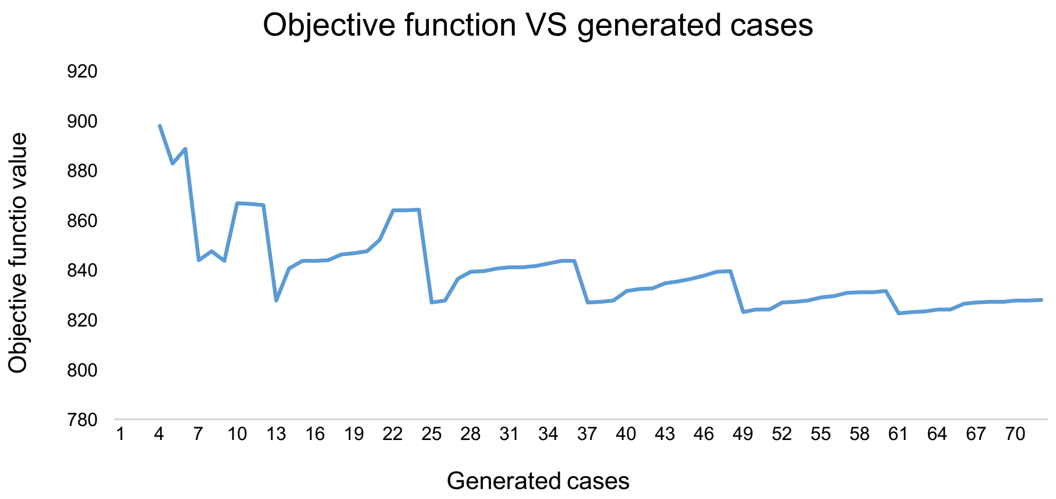


Figure 21. Minimization evolution of the Objective function in a 6 generation analysis

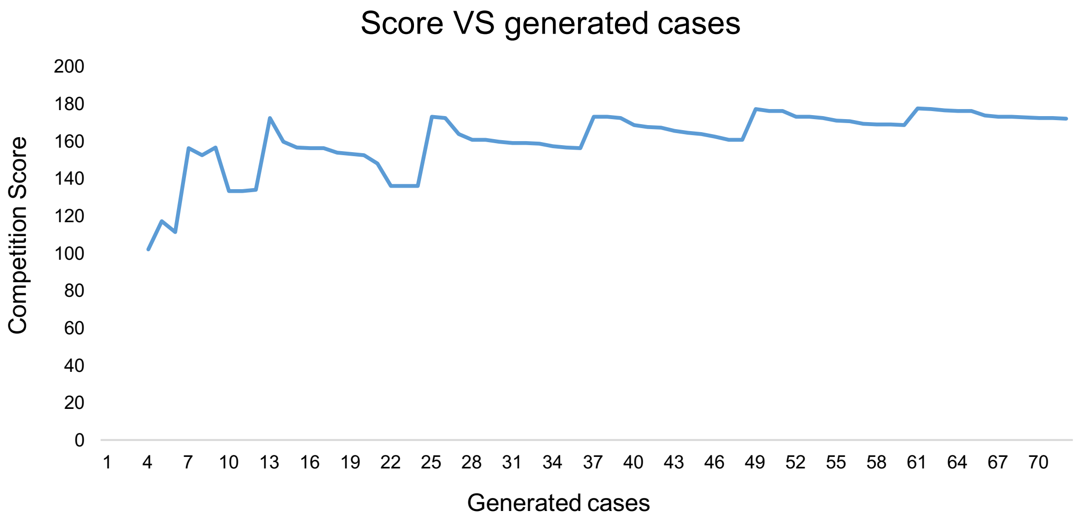
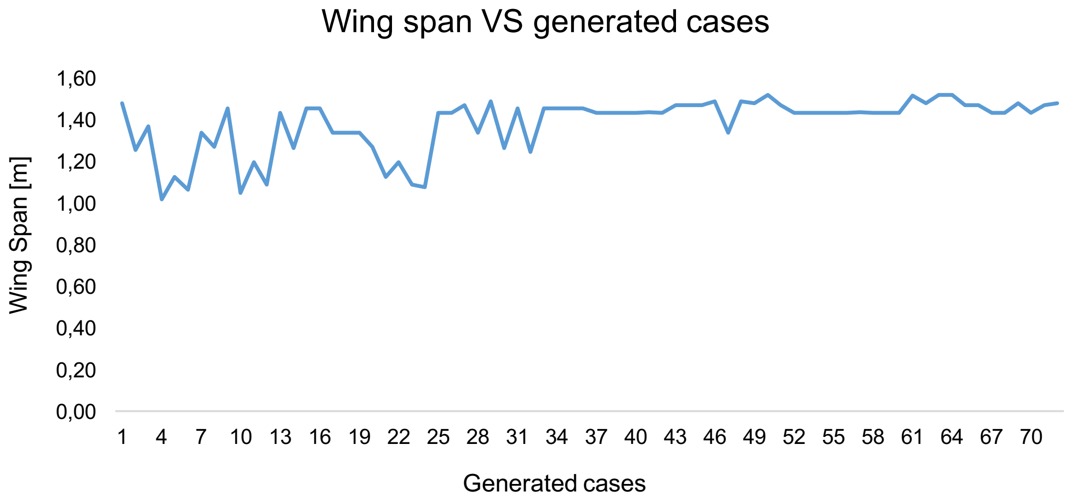
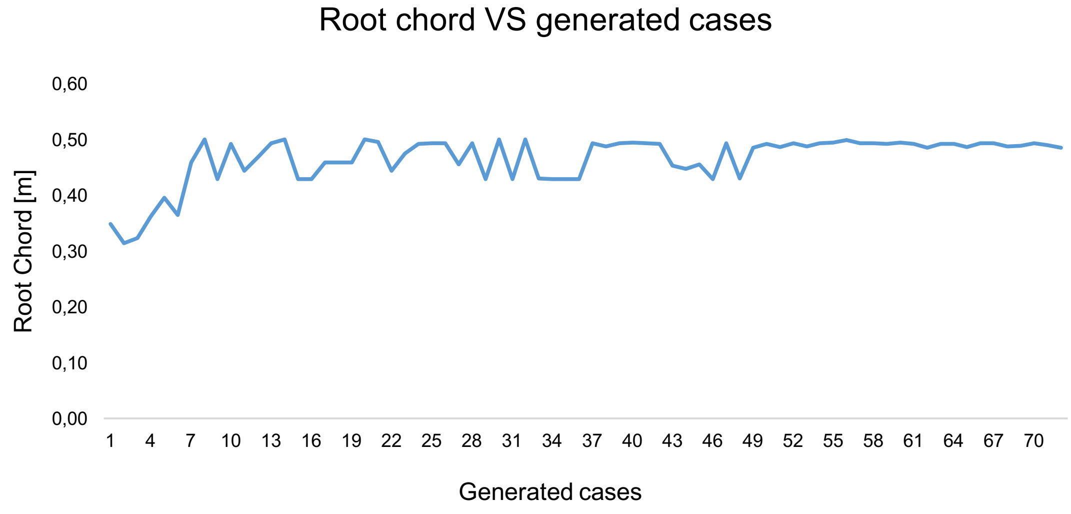


Figure 22. Maximization evolution of the competition score in a 6 generation analysis

Having doubled the generations and so the number of generated cases, the results are much more concluding. An evolution pattern is clearly generated and the optimization process seems to be consolidating. However, there are still too many few analysed cases, so the optimal solution can not be deciphered yet.

Figure 23 shows the relation between the geometry of the wing and the generated cases:





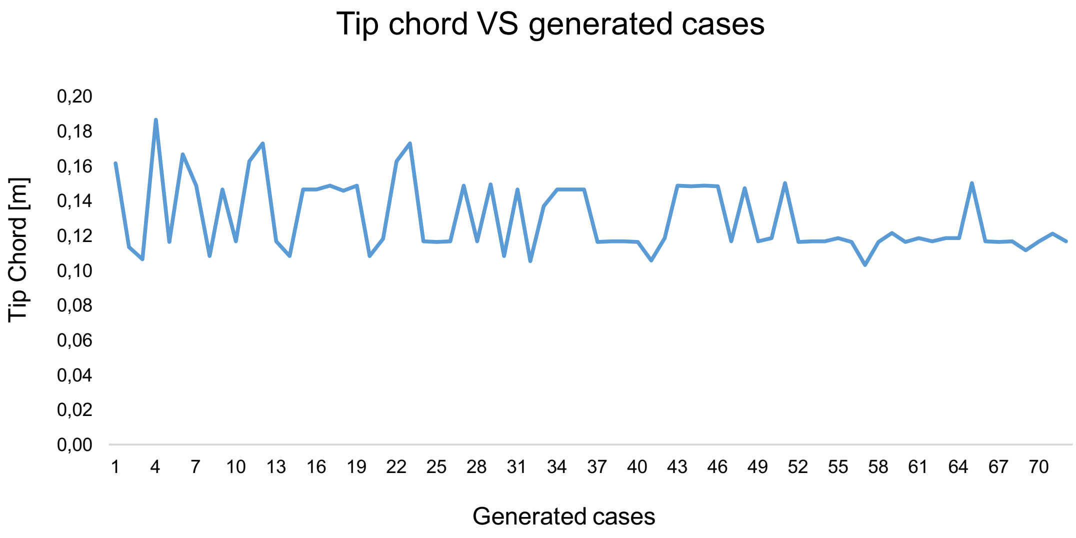


Figure 23. Evolution of the geometry of the wing in a 6 generation analysis

Both the wing span and the root chord tend to maximize their magnitude as the optimization progresses. In the other hand, the tip chord value does not follow a clear pattern, although smaller values seem to have better results. Despite the results might not be concluding enough, with the 6 generation optimization process a first approach to the final solution might be found, with the advantage of having a short calculation time.

The maximum value of the competition score (equivalent to the minimum value of the objective function) with the corresponding wing geometry that has been obtained in the 6 generations optimization process is (Table 4):

Score	Wing Span	Root Chord	Tip Chord
177,35	3,03	0,49	0,12

Table 4. Best score and wing geometry in the 6 generations optimization process

Pictures of the optimum wing planform in the 6 generation optimization process are shown below (Figure 24 and Figure 25):

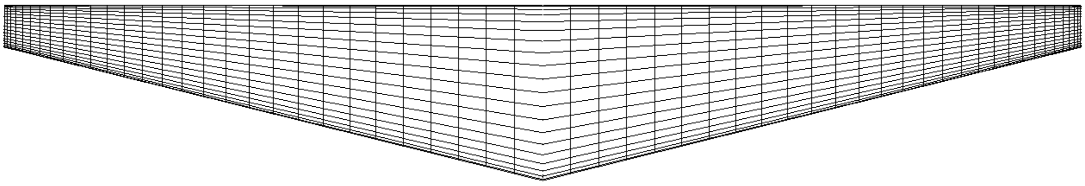


Figure 24. Optimum wing planform obtained from the 6 generations optimization process

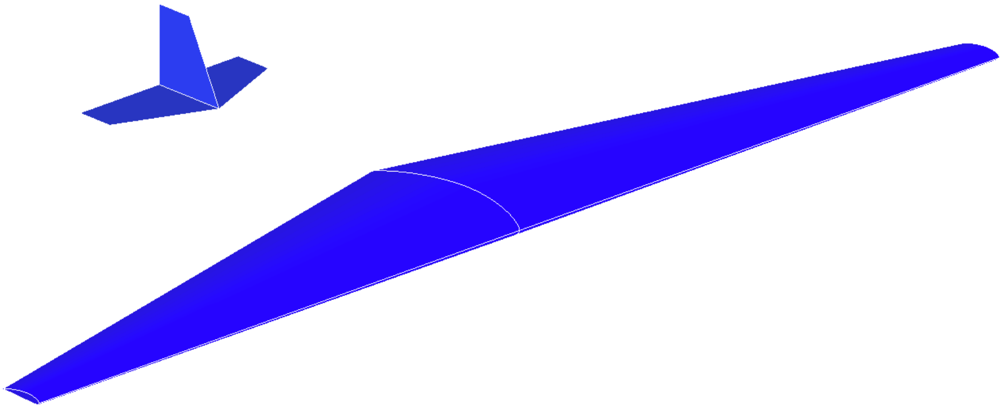


Figure 25. Conceptual design of the aircraft obtained from the 6 generations optimization process

12 Generations Optimization

With Figure 26 and Figure 27 it is intended to show the optimization process of the objective function and the competition score, in a 12 generation analysis. Each generated case is a combination three values of the design variables (wing span, root chord and tip chord) which define the wing geometry.

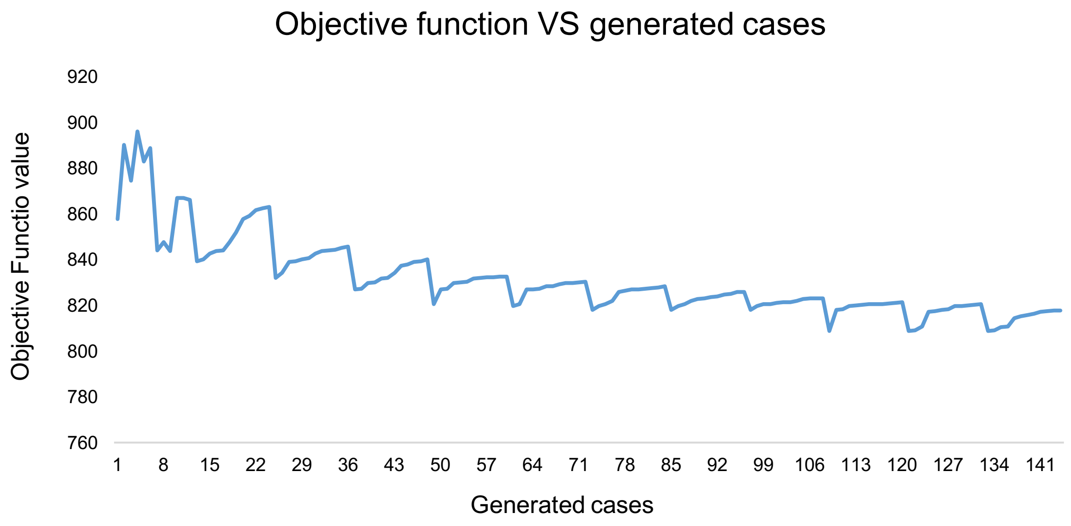


Figure 26. Minimization evolution of the Objective function in a 12 generation analysis

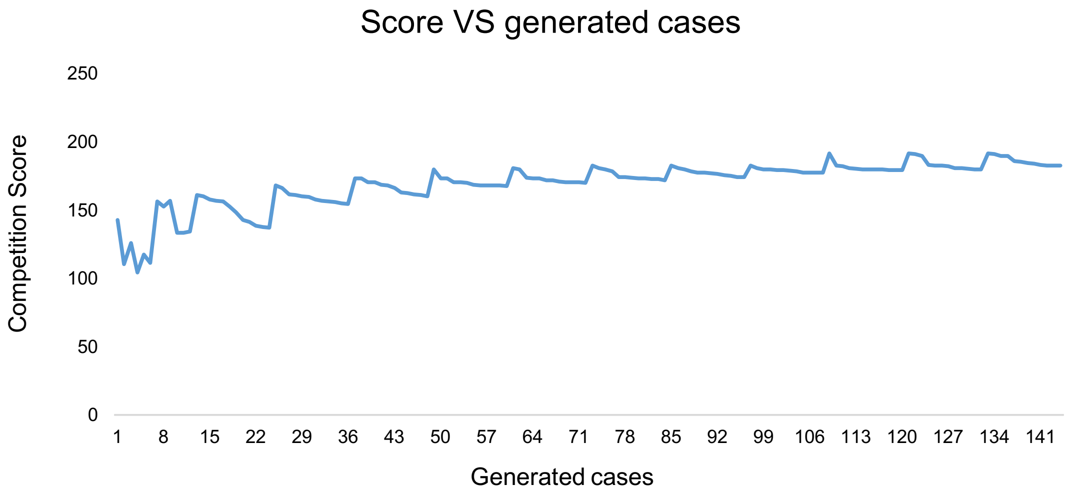
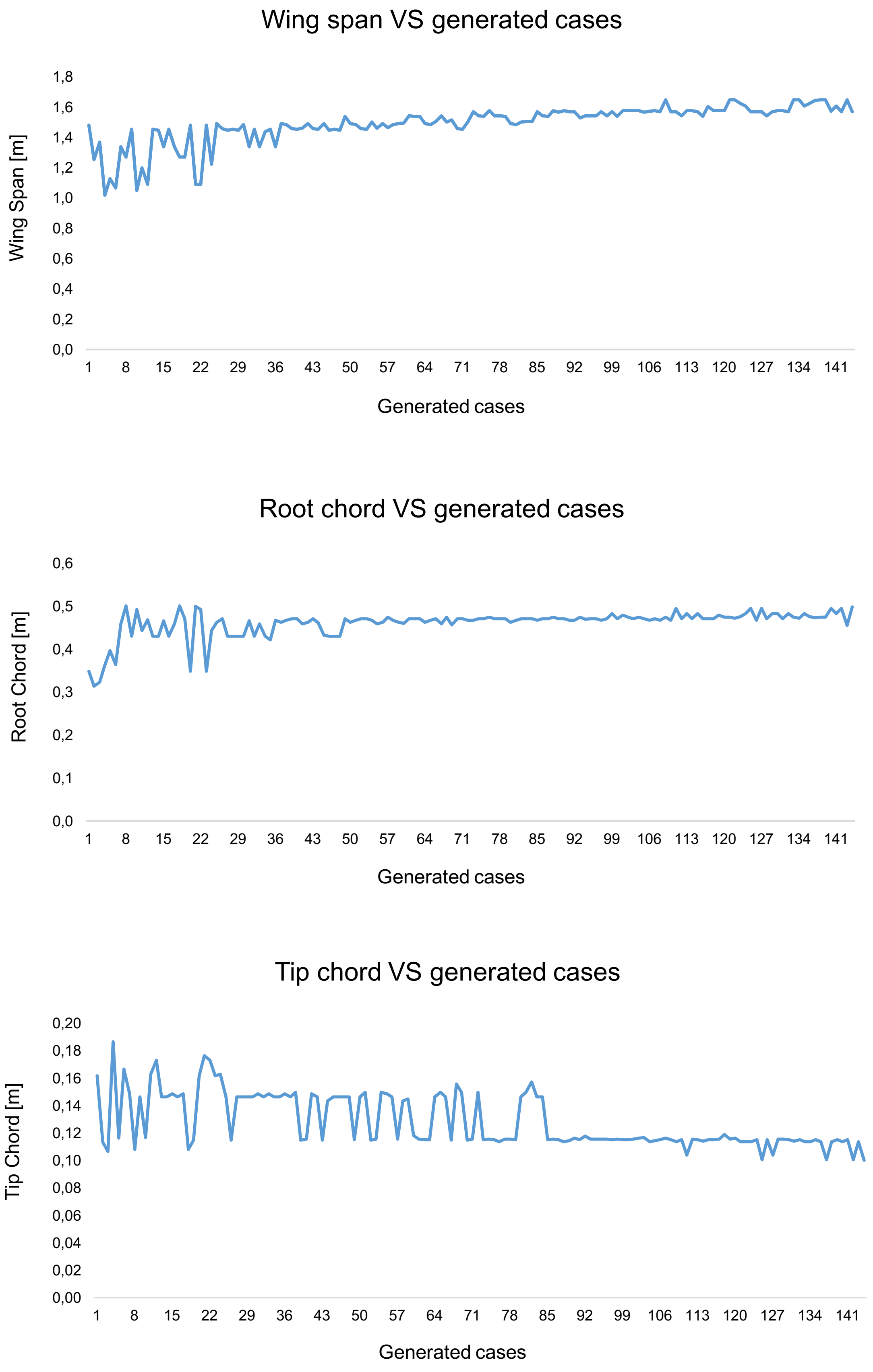


Figure 27. Maximization evolution of the competition score in a 12 generation analysis

As the results show, the 12 generation optimization process might be the first fully conclusive analysis. A higher time is required, but the maximization of the competition score seems to have reached its upper limit.

Figure 28 shows the relation between the geometry of the wing and the generated cases:


Wing span VS generated cases

Root chord VS generated cases

Tip chord VS generated cases

Figure 28. Evolution of the geometry of the wing in a 12 generation analysis

Regarding the geometry of the wing, the results are also clear: the bigger the wing span and the root chord are, the better is the competition score; and the smaller the tip chord is, the higher is the score.

At this point, the optimization process could be ended, and good results could be exposed. However, it is convenient to perform a mesh refinement and a higher generation analysis will be done.

The maximum value of the competition score (equivalent to the minimum value of the objective function) with the corresponding wing geometry that has been obtained in the 12 generations optimization process is (Table 5):

Score	Wing Span	Root Chord	Tip Chord
191,19	3,29	0,47	0,11

Table 5. Best score and wing geometry in the 12 generations optimization process

Pictures of the optimum wing planform in the 12 generation optimization process are shown below (Figure 29 and Figure 30):

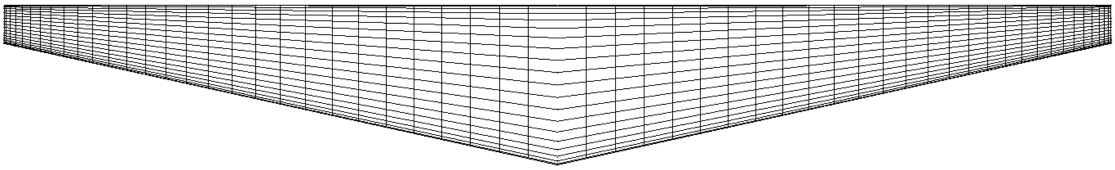


Figure 29. Optimum wing planform obtained from the 12 generations optimization process

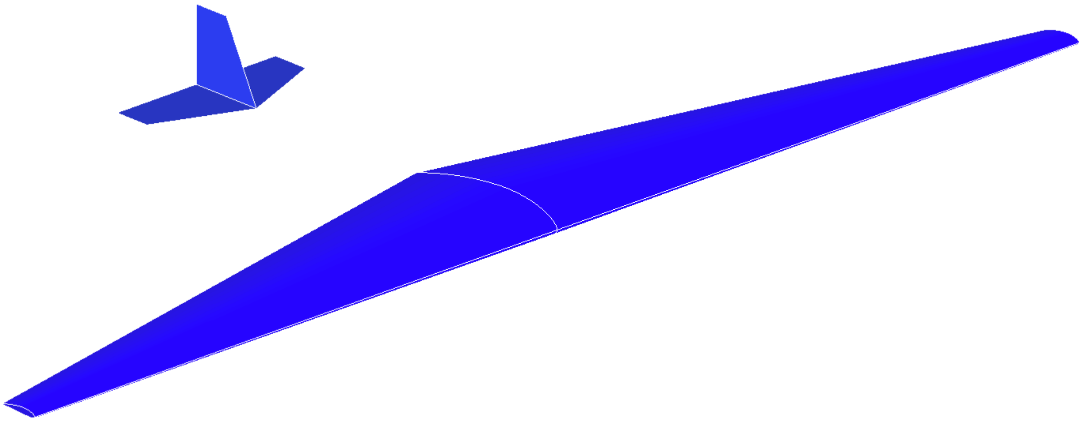


Figure 30. Conceptual design of the aircraft obtained from the 12 generations optimization process

24 Generations Optimization

With Figure 31 and Figure 32 it is intended to show the optimization process of the objective function and the competition score, in a 24 generation analysis. Each generated case is a combination three values of the design variables (wing span, root chord and tip chord) which define the wing geometry.

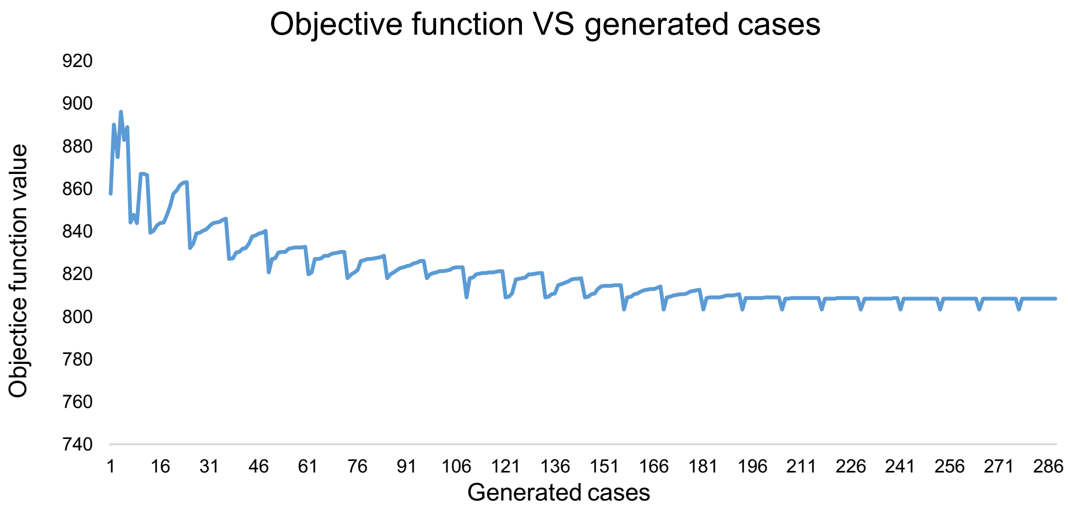


Figure 31. Minimization evolution of the Objective function in a 24 generation analysis

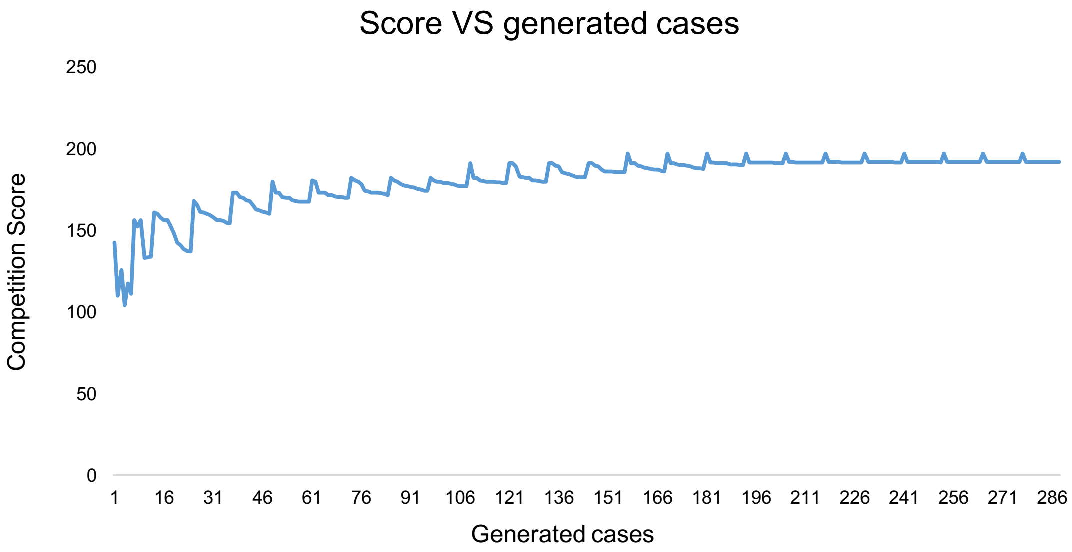
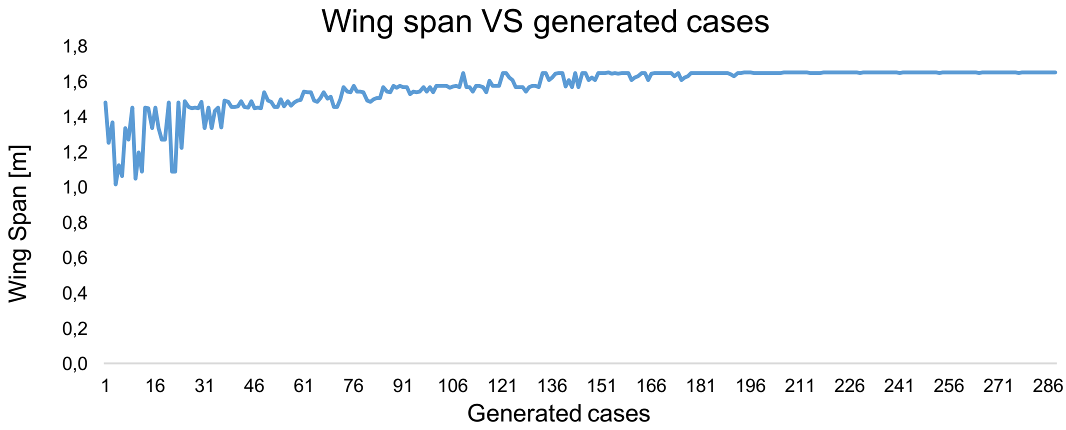
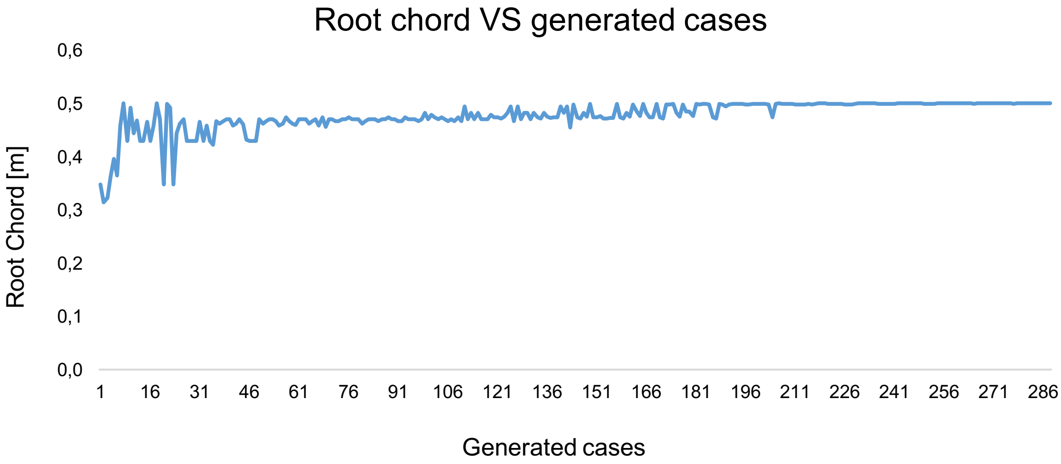


Figure 32. Maximization evolution of the competition score in a 24 generation analysis

The optimization has clearly reached its limit, because the minimizing of the objective function value has stalled. The results seem not to get better if more generations are calculated.

Figure 33 shows the relation between the geometry of the wing and the generated cases:





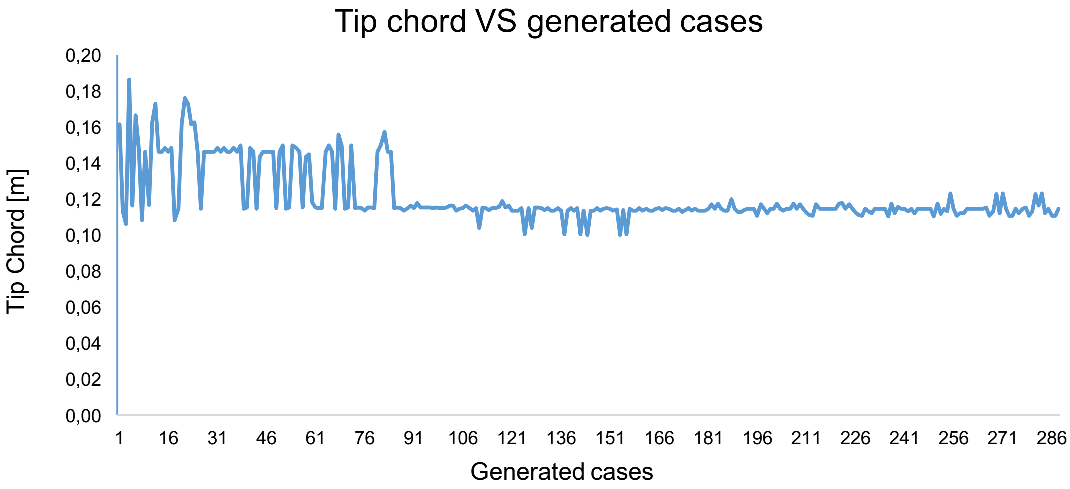


Figure 33. Evolution of the geometry of the wing in a 24 generation analysis

With the 24 generations analysis an optimal geometry of the wing can be extracted. The results do not vary much compared to the 12 generations analysis, but allow to add a security factor that the previous process did not provide.

The maximum value of the competition score (equivalent to the minimum value of the objective function) with the corresponding wing geometry that has been obtained in the 24 generations optimization process is (Table 6):

Score	Wing Span	Root Chord	Tip Chord
196,98	3,29	0,50	0,11

Table 6. Best score and wing geometry in the 24 generations optimization process

Pictures of the optimum wing planform in the 24 generation optimization process are shown below (Figure 34 and Figure 35):

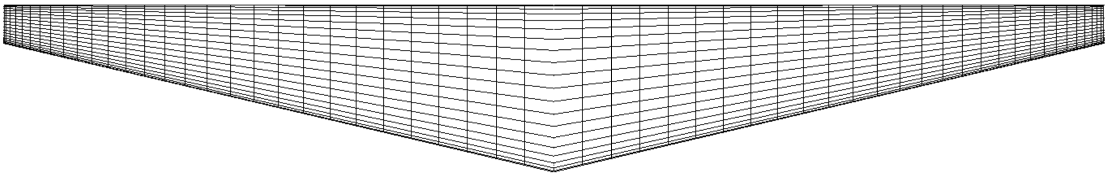


Figure 34. Optimum wing planform obtained from the 24 generations optimization process

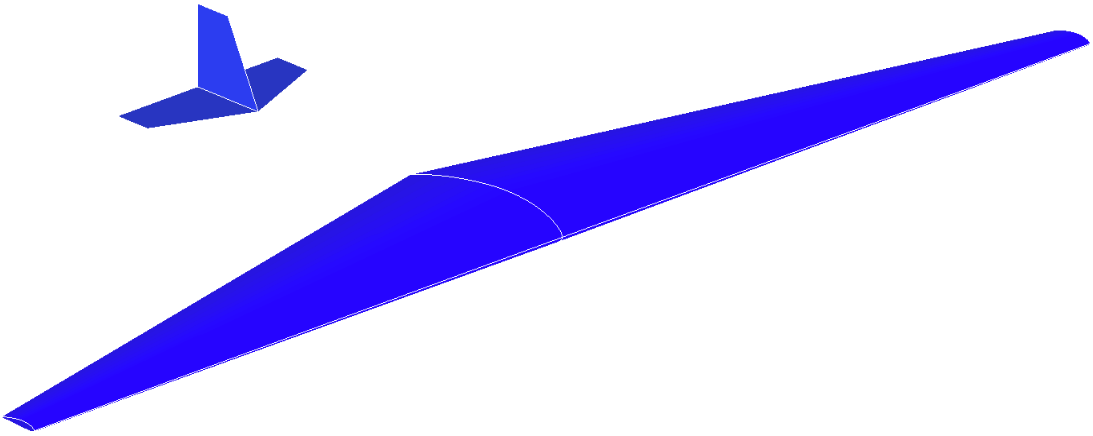


Figure 35. Conceptual design of the aircraft obtained from the 24 generations optimization process

Optimal wing planform

The evolution of the wing planform is conclusive enough after the 24 generations optimization process with NSGA-II. The results show a clear tendency of either the wing span, root chord and tip chord in order to maximize the competition score, or equivalently, minimize the objective function.

As shown in Figure 36 and Figure 37, a big values of wing span and root chord are required if the score wants to be maximized:

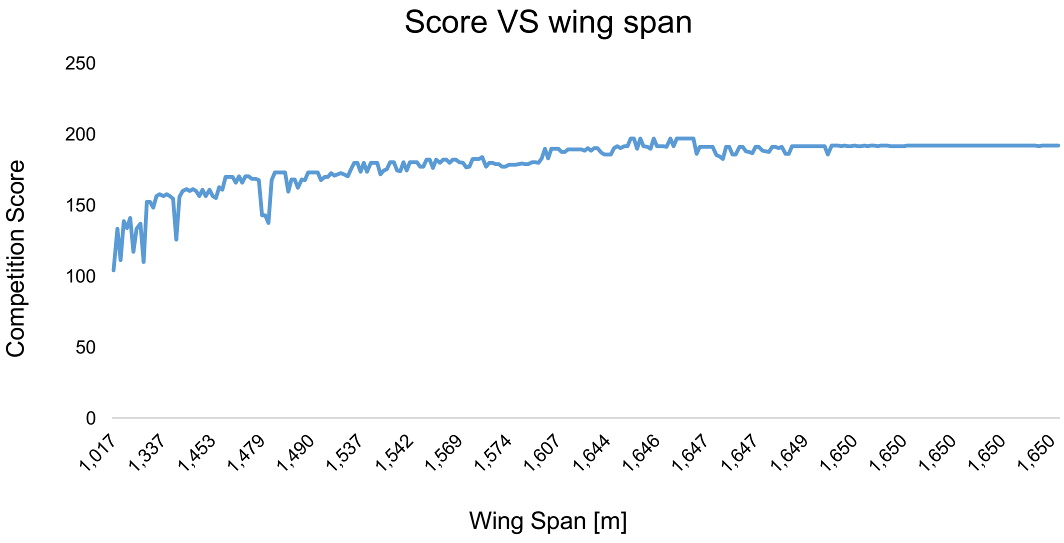


Figure 36. Relation between the competition score and the wing span

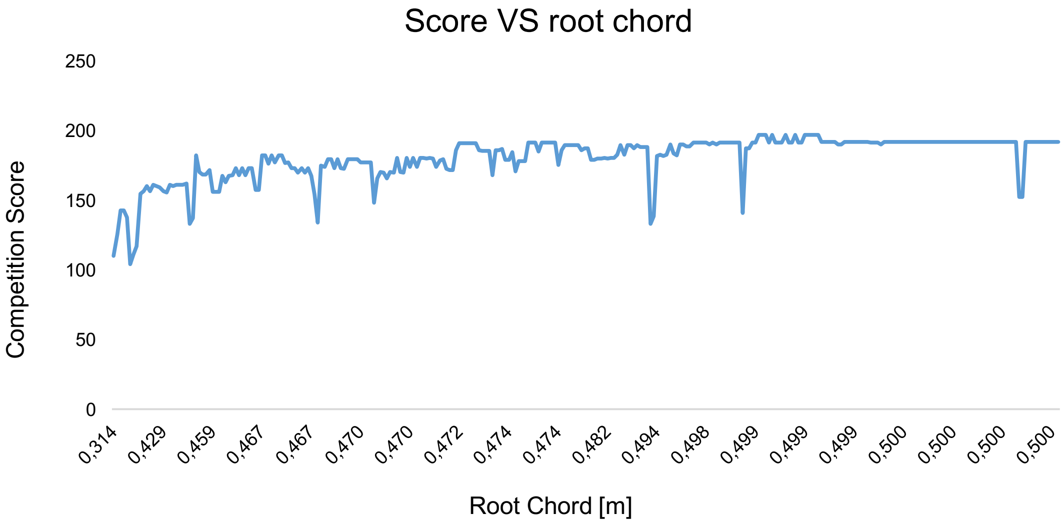


Figure 37. Relation between the competition score and the root chord

On the other hand, and contrary to what could have been expected, small tip chord values provide better results (Figure 38). Although this geometry parameter does not have a tendency as conclusive as the others, it is clear that big tip chord values do not provide good results.

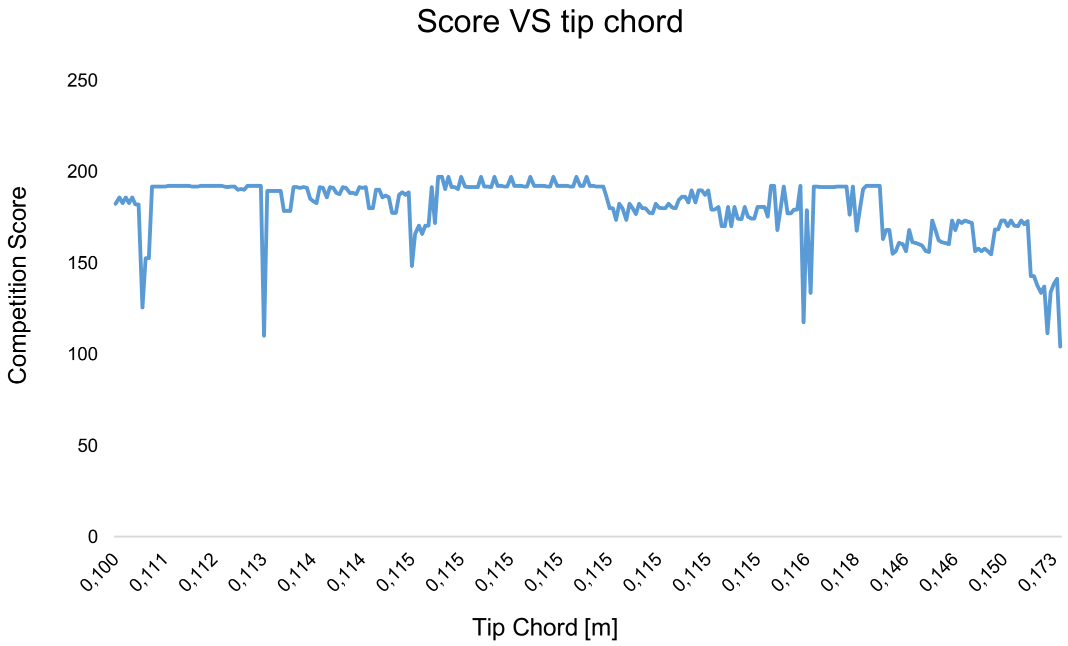


Figure 38. Relation between the competition score and the tip chord

So the final election of the wing planform is the one obtained with the last optimization process (24 generations). Table 7 show the best result in each generation analysis:

Generations	Best Score	Wing Span	Root Chord	Tip Chord
3	167,93	2,98	0,46	0,15
6	177,35	3,03	0,49	0,12
12	191,19	3,29	0,47	0,11
24	196,98	3,29	0,50	0,11

Table 7. Comparison between the geometry and the score of the best wing configurations

And finally, in order to have a visual concept of the wing optimization process, all generated planforms are exposed in Figure 39:

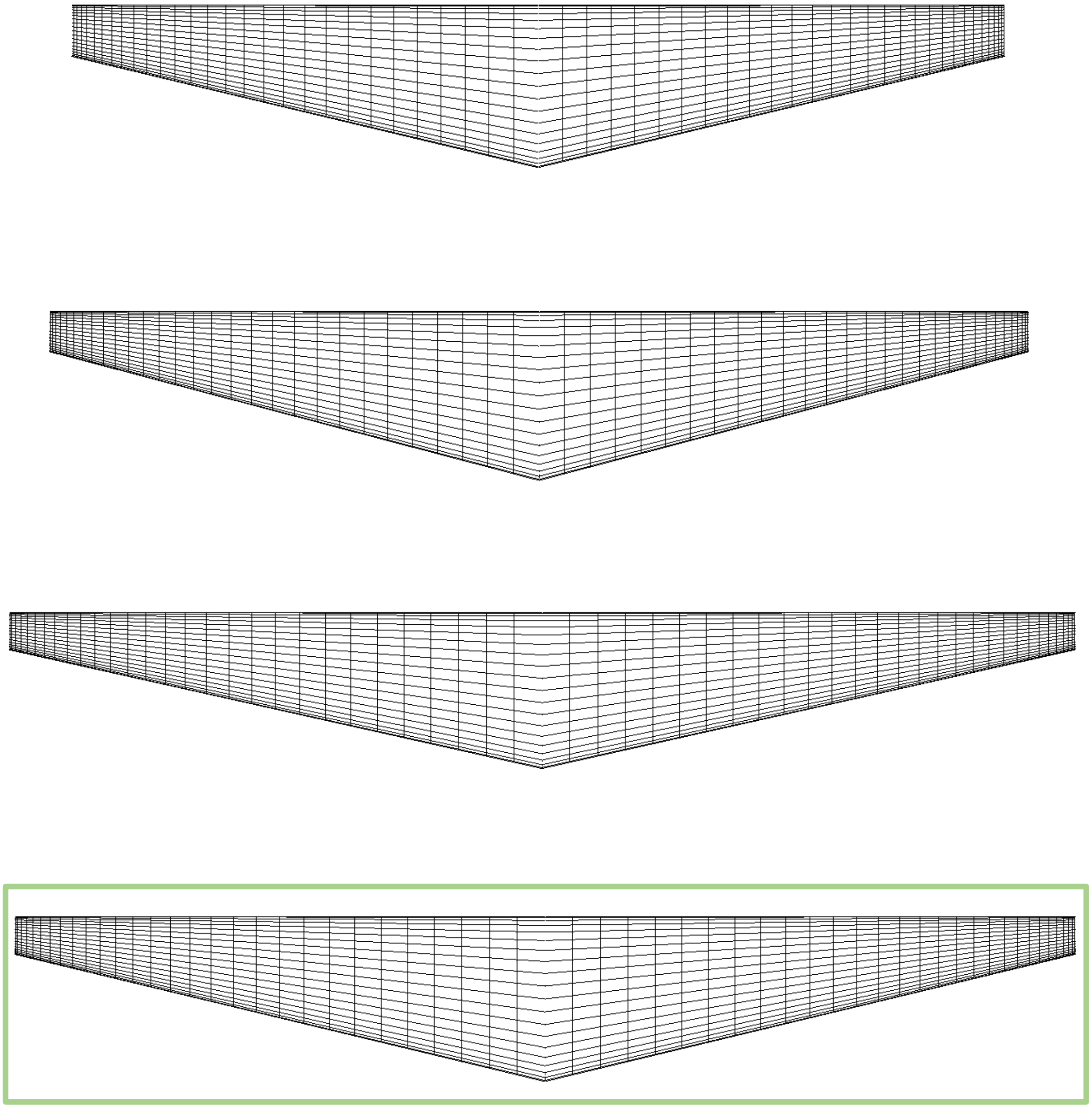


Figure 39. Wing planforms of the best wing configurations, ordered from least to most generations

Initially, short and narrow wings are generated, with a bigger tapper ratios. But it has been demonstrated that the best solution for the Air Cargo Challenge 2015 competition is an aircraft with a big wing surface, but a small taper ratio.

Next phase planning

A continuity of this study is required in order to be able to obtain a more detailed design of the optimal wing planform of and aircraft for the Air Cargo Challenge 2015 edition. Next planned steps are the following:

- Design variable number increase. The geometry of the wing can be defined by more parameters and not only the ones used in this study:
    - The wing can be divided into more sections. The more sections it has, the more detailed the planform will be.
    - For each section, a chord value has to be defined as a design variable.
    - The leading edge of the wing will not be aligned in the same imaginary line. It is desired to have a different offset for each wing section in order to match the maximum thickness point of all sections. It will allow an optimal structural design, as inertia moment will be maximized.
- Aircraft stability is not contemplated in this study, but is an essential part of the aerodynamic design process. So the following points should be added in future modifications:
    - Horizontal and vertical stabilizes design for longitudinal and lateral-directional stability must be designed. To do so, tail volume and C_M-α coefficients analysis will be introduced into the code.
    - The wing dihedral parameter must be contemplated, as well.
- Mesh refinement. Although the geometry of the wing can have a fixed section number, for the aerodynamic analysis the wing can be divided into as many panels as the user prefers. The higher the number of panels, the more reliable the results will be.
- And finally, the program should be easily modified in order to adapt it to future Air Cargo Challenge editions, as regulations will be certainly modified.

Economic feasibility and environmental impact of the study

Being a study and not a project, the budget in the economic feasibility contemplates only the required hours of labour force, as well as the used hardware and electricity.

According to ***(10)*** and ***(11)*** the budged for this study is presented below (Table 8):

Activity / Material	Time [h]	Energy [KWh]	Cost/time [€/h]	Cost/Energy [€/KWh]	Industrial cost [€]	Price [€]
Programming	180	-	30	-	-	5400,00
Results analysis	70	-	30	-	-	2100,00
Report redaction	50	-	30	-	-	1500,00
Computer	-	-	-	-	1000	1000,00
Electricity	300	0,3	-	0,124107	-	11,17

Total Price	**10.011,17 €**

Table 8. Budget of the study

Because of the imperative need to use the computer for the development of this study, this entails an environmental impact due to electricity consumption. However, for future aircraft design projects, with this tool the calculation time will be dramatically reduced, a fact that leads to energy saving.

Conclusions

The aim of this study was to develop a computer tool to optimise the design of a wing for a specific mission aircraft. Not only the aerodynamic properties of the wing have been studied, but also an optimization process has been performed using the multi-objective function optimization algorithm NSGA-II. This program aims to be an essential designing tool for Trencalòs Team during its preparation for the International Competition Air Cargo Challenge 2015, held in Stuttgart.

The experience and knowledge that I have obtained as member of Trencalòs Team during the last three years has been essential for the development of this study. Despite the programs used are not the ones that Trencalòs Team uses during their designing process, the mathematical bases and formulation are the same so the results will be considered reliable enough for their implementation.

All proposed objectives of the study have been successfully achieved and the development of the software leads not only to a new designing tool but also to really helpful results, which will be decisive for Trencalòs Team during the aircraft design for the competition. With this study it has been demonstrated that big aircrafts which stand out for having a higher MTOW are the best solution for the Air Cargo Challenge 2015 competition, rather than small aircrafts with high maximum velocities. However, although the carried payload is probably the most important factor in the competition formula, flight performance and maximum speed shall not be set aside, as this study has been done with a standard airfoil (NACA 4415), whose aerodynamic properties are not outstanding (high lift coefficient, low drag coefficient or good aerodynamic efficiency, etc.). Thus, high lift airfoils, which have been used in the competition until 2015's edition, might not be suitable for this mission, due to their huge drag coefficient and easy stall condition.

Finally, the continuity and expansion of the program turns to be essential after the 2015 edition of the competition; otherwise, this tool would become outdated and useless and no benefit could be obtained.

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