# New Aircraft Concepts for Improved Environmental and Energetic Efficiency

João Gonçalo Magriço Ferro
joao.g.m.ferro@ist.utl.pt

Técnico, Lisboa, Portugal

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**Abstract**

Eco-efficiency has become the the main design driver in the development of new and future aircraft transportation systems. In this thesis, new aircraft design concepts are studied to quantify the benefits of new configurations.

The work developed aims to verify the concepts that were proposed by the OEM sponsoring the NewFace project. Aerodynamic considerations, new propulsion systems and new materials are some of the enabling technologies considered in the design of new configurations.

During this process, it has become evident that in order to achieve the objectives required for greening aviation, it is necessary to have an integrated optimization framework that includes all disciplines and their interactions.

**Keywords:** Aircraft, Design, Eco-efficiency, STOL, Jet propulsion.

## 1. Introduction

Air Transportation had a significant positive impact in the 21th century and will continue to have in the future. This mode of transportation provides a safe, fast and efficient transportation for long distance travel, unmatched by any other long distance travel [1]. But this mean of transportation its one of the biggest polluters.

The work developed in this thesis address eco-efficiency as one of its main drivers since that it will be the key to maximize the operators return on investment (ROI) on the choice of new aircraft.

This work is developed as a result of a contract between IDMEC and Alma Design, with the main objective to do the preliminary design of the three concept aircraft that will be developed in the project newFACE.

### 1.1. Project NewFACE Motivation

The main objective of this project is to develop new aircraft concepts and solution, for the year 2035, through conciliation of the two main factor that will influence the aviation of the future:

- The search for better efficiency, mainly environmental and energetic;
- the need to develop new aircraft more centered in operation and passengers needs.

In the definition of the new aircraft a Design Thinking methodology was used. This methodology allowed the guidance of the creative process and multidisciplinary management. The multidisciplinary needed for the methodology was obtained by the collaboration of all the entities, participating in project NewFACE, in the design process, with their different skills. This allowed knowledges in design, engineering, manufacturing processes, materials, among others.

### 1.2. Participation in the Design Group

The work developed by the author, in the design team, can be divided in two works, the interaction with all the design team, as the aerospace specialist, and the development of the conceptual aircraft project.

### 1.3. Environmental and Economic Drivers

In the foreseeing future the aircraft traffic will increase, with some prediction of up to 4% or more per year, this increase in traffic will lead to more airport restrictions - taxes and limitations - due to noise and pollution.

In the last years, the fuel became the major cost in the airlines cost structure, it can now represent 40% to 50% of their operational costs.

## 2. State of the art

In this section are presented the state of the art (SOA) concepts, developed by the major player, as well as the SOA technologies that can support the aircraft eco-efficiency, mainly in aerodynamics and propulsion.

### 2.1. Aircraft manufacturer vision

The vision of Boeing, at [1], presented four aircraft for 2030, the Refined SUGAR, the SUGAR High, the SUGAR Volt and the SUGAR Ray. In [1] was also presented their vision for the air traffic management (ATM). Airbus presented its vision in the The Future by Airbus [**?**]. In this work Airbus presented their vision for ATM, with the *Smarter Skies*, and for the future aircraft, with the *Concept Plane*. In the *Concept Plane* are only presented the technological advances featured in the concept.

In this work is also important to make reference to the a electric aircraft being developed by Voltair, an Airbus subsidiary, and to the AirMule, an VTOL concept, with two ducted fans, that's going to be useful as support for one of the concepts.

### 2.2. Aerodynamics

In this section is presented a brief description of the aerodynamic improvements that can help reduce the drag of the configurations, by maintaining laminar flow longer, increasing the efficiency and reducing the amount of fuel burned.

To extend the laminar flow over the wing, three flow control methods can be implemented: the natural laminar flow (NLF), the laminar flow control (LFC) and the hybrid laminar flow control (HLFC).

#### 2.2.1 Flow Control

In this subsection are presented some of the active and passive technologies that enable the flow control. First are presented the passive technologies, followed by the active technologies. In the passives technologies the NLF airfoils and wings, the discrete Roughness Elements (DRE), the Gaster bumps and the surface deturbulator, can be implemented. In the active technologies can be used suction, Dielectric Barrier Discharge (DBD) actuator, laminarturbulent transition delay by local surface heating in the nose of the body, Boundary layer development control by excitation of artificial "turbulent spots" and adaptive wings.

### 2.3. Propulsion

In this section it's made a presentation of today's engines manufactured by the major players in the market, followed by trends for the future engines, with an brief description of the energy sources possible to power those engines. In this section is also made a brief introduction of the future possibilities in auxiliary power units (APUs).

Are presented the Trent 7000, from R&R, the GEnx, from GE, the PW1000G, from P&W, and the Silvercrest, from Snecma.

For the foreseen future the the turbofan is going to evolute in the two direction, the direct drive turbofan (DDTF) and the geared turbofan (GTF), with higher bypass ratio (BPR) than todays DDTF and GTF. Other engine that, in last years, had a big development effort redirected to him was the counter rotating open rotor (CROR). Other big tendency in aircraft engines is the attempt to electrify the aircraft propulsion. An example of this is the *hFAN* engine presented in [1], and the electric aircraft being developed by Airbus.

In addition to the electric energy sources, the full electric or the hybrid, are being studies other alternatives energy sources like the biofuels, the liquefied natural gas and the hydrogen. This is the fuel being study, by Airbus and DLR, to power a new fuel cell APU.

## 3. Support Material

In this chapter it's presented the material developed, by the author, in order to respond to the consortium needs, in the course of the project.

### 3.1. Application (APP) motivations

This APP was developed as a request, by Embraer, in which was intended to have a software that allowed for a rapid calculation of the Maximum Take-Off Weight (MTOW) in the meetings. This software would enable to recalculate the MTOW just with a slide of a bar that represented one of the parameters. The application has also the ability to assist in the selection of wing area and propulsion needed for each configuration by a constraint diagram.

### 3.2. APP Theoretical bases

In the next two subsection are presented the theoretical background of the methods applied in the APP.

#### 3.2.1 Maximum Take-Off Weight (MTOW)

The preliminary estimate of the MTOW is obtain by the methodologies presented in [2, chapter 2]. In this methodologies the MTOW is calculated from the iterative method presented in figure,

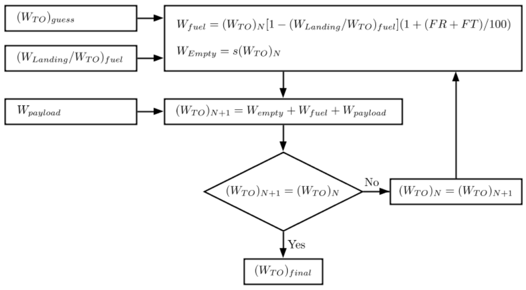


Figure 1: Algorithm for the calculation of the MTOW.

wherw $W_{TO}$ is the MTOW, $s$ is the structural factor and $(W_{landing}/W_{TO})$ is defined by,

$$(W_{landing}/W_{take-off})_{fuel} = \frac{W_2}{W_1}\frac{W_3}{W_2}\cdots\frac{W_N}{W_{N-1}}. \quad (1)$$

where the $W_f/W_i$ for each segment, of the mission, is defined by,

| Mission segment | $W_f/W_i = R_f$ |
|---|---|
| Start-Up & Take-Off | $0.97 \leq Rf \leq 0.975$ |
| Climb & Accel. Cruise | $R_f = 1 - .04M_{cr}$ [1]; $M_{cr} < 1$ |
| Cruise | Worked up Breguet Equation $R_f = \exp\frac{-RC}{V(L/D)}$ [2] |
| Holding | Worked up Endurance Equation $R_f = \exp\frac{-EC}{(L/D)}$ [2] |
| Landing | $0.97 \leq R_f \leq 0.975$ |

Table 1: Fuel fractions for each section of the mission.

where $C$ or $SFC$ is the specific fuel consumption, the $L/D$ is the Lift-over-Drag, $M_{cr}$ is the cruise mach, $V$ is the segment speed, $R$ is the range required for the mission and $E$ is the loiter time.

### 3.2.2 Constraint Diagrams

Aircraft constraint diagram is a diagram in which are represented the limits imposed to any aircraft design. In this methodology is possible to choose a Design Point (DP), in the Design Space (DS) , from which is possible to obtain the Thrust-to-Weight ratio $(T_{SL}/W_{TO})$ and Wing Loading $(W_{TO}/S)$. The equations from which the constraint curves are plotted are presented in table 2, a list of the parameters,used in table 2 is also presented.

[1]For $M_{cr} \geq 1$ , $R_f = 0.96 - .03(M_{cr} - 1)$. Approximation in two linear segments of the figure 2.3 of ref. [2].

[2]Only valid para turbojet,turbofan and Ramjets.

| Requirement | |
|---|---|
| Take-Off | $\frac{T}{W} \geq \frac{A_1^2}{2C_{Lmax}}[\frac{2}{\rho g s_{TO}}(\frac{W}{S})+$ $+(C_{D_0} - \mu C_{Lmax} + KC_{Lmax}^2)] + \mu$ |
| Climb angle | $\frac{T}{W} \geq \sin\gamma + 2\sqrt{C_{D_0}K}$ |
| Cruise Speed | $\frac{T}{W} \geq \frac{\rho V^2 C_{D_0}}{2(W/S)} + \frac{2K}{\rho V^2}(\frac{W}{S})$ |
| Range | $\frac{W}{S} = 0.5\rho V^2\sqrt{\frac{C_{D_0}}{3K}}$ |
| Holding | $\frac{W}{S} = 0.5\rho V^2\sqrt{\frac{3C_{D_0}}{K}}$ |
| Max Ceiling | $\frac{W}{S} \leq 0.5\rho V^2\sqrt{\frac{C_{D_0}}{K}}$ and $\frac{W}{S} = 0.5\rho V^2 C_L$ |
| Sustained Turn | $\frac{\frac{W}{S} \leq [(\frac{T}{W}) \pm \sqrt{(\frac{T}{W})^2 - 4n^2 CD_0 K}]}{(\frac{4Kn^2}{\rho V^2})}$ and $\frac{T}{W} \geq 2n\sqrt{C_{D_0}K}$ |
| Landing | $\frac{W}{S} \leq \frac{\rho g}{2}(s_L - \frac{h}{\tan\gamma})[\frac{2\mu C_{Lmax}}{A_2^2}+$ $+(C_{D_0} - \mu C_{Lmax} + KC_{Lmax}^2]$ |

Table 2: Constraint Diagram equations.

| | | |
|---|---|---|
| $C_{L_{max}}$ | - | Maximum lift coefficient; |
| $C_{D_0}$ | - | Minimum 3D drag coefficient; |
| $s_{TO}$ | - | Take-off distance; |
| $\mu$ | - | Rolling coefficient (with brakes for landing); |
| $K$ | - | "Drag due to Lift" as in [5, page 455] |
| $n$ | - | Load factor; |
| $s_L$ | - | Landing distance; |
| $\gamma$ | - | Climb angle |
| $V$ | - | Velocity for each phase. |

### 3.3. APP UX

In order to get a more intuitive application the author developed the application on the operating system(OS), ANDROID™.

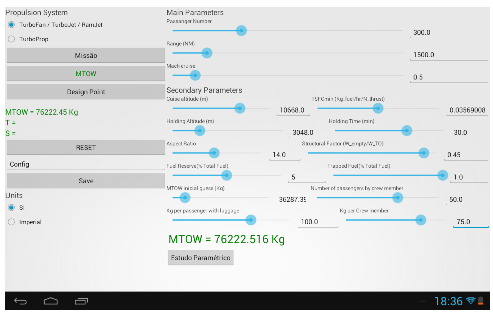


Figure 2: Screenshot of the application MTOW tab.

When the user opens the applications, an user interface (UI) is open. In this UI the user has access to the three main tabs, the tab with the percentages of fuel for the mission segments, the tab where is possible to choose the parameters for the calculation of the MTOW, figure 2, and the tab where is possible to create constraint diagrams. In the left side is also given the possibility to choose from different propulsion modes - Jet or Propeller - and change the units between SI and IMP units. The user is also presented with the calculated MTOW, $S$ and $T$, when they are calculated.

### 3.4. APP Studys

In order to demonstrate the quality and precision of the method and application three type of tests were performed. A Comparison, a Coherency and a Consistency tests, that are explained in the next sub-sections.

#### 3.4.1 Comparison

A comparison of the results obtained by the application and the results gave by a spreadsheet, that is given as support material of reference [2], was executed. The difference between the two MTOW calculated is 0.0%.

#### 3.4.2 Coherency

In this section is verified the coherency of the methodology and application, by calculating the MTOW of an commercial aircraft, an Airbus A320. The difference between the two values is very small, about 3.8%.

#### 3.4.3 Consistency

To verify the consistency of the application, the calculation of the same input parameters were repeated several times in order to understand if the were any differences in the result. After several tests the consistency of the application was verified, there wasn't any difference between the calculated MTOW's.

## 4. Conceptual Design Study

In this chapter are presented the design drivers, the design decisions, and the calculations made to verify the configurations created in the course of the project Newface.

### 4.1. Design drivers

As referred in section 1 the main objective of this thesis is the development of the Aircraft Design of the concepts developed in project NewFACE. In this project was decided to study three aircraft, one of them with 2 different propulsion systems. A medium range commercial aircraft for 150 PAX, the Box-wing, with a turbofan and a CROR. A long-rang business jet, the V-tail, and an general aviation aircraft, the Utility, with STOL capabilities, given by lift fans on the wings.

### 4.2. Initial Layout

In this section are presented and discussed the main decision, as well as technologies implemented in the aircrafts, in order to achieve the main objectives of the project.

#### 4.2.1 Mission definition

The first calculations of the MTOW require the definition of a mission. The most important parameters to be defined are the range (R) and the holding time (HT), presented in table 3.

| | | Aircraft | | |
|---|---|---|---|---|
| | | Box-wing | V-tail | Utility |
| R | km | 7408 | 9260 | 926 |
| | (NM) | (4000) | (5000) | (500) |
| HT | min | 30 | 30 | 0 |

Table 3: Mission definition.

For the fractions of the $W_f/W_i$ for take-off and landing was used the maximum value presented in [2, condition 2.5 and 2.22], 3% .

#### 4.2.2 Take-off weight estimation

With the values for all the parameters, decided by the design team, , using the application was calculate an initial MTOW for each aircraft. The calculated values of MTOW, for each aircraft, are presented in table 4.

| | Aircraft | | |
|---|---|---|---|
| | Box-wing | V-tail | Utility |
| kg | 62030.2 | 28013.5 | 3239.3 |
| (lb) | (136753.1) | (61759.2) | (7141.4) |

Table 4: MTOW Output.

#### 4.2.3 Constrain diagrams

The values of thrust and wing area calculated using the APP are presented in table 5. The thrust predicted for the Utility doesn't include the power needed for the lift-fans.

| | Aircraft | | |
|---|---|---|---|
| | Box-wing | V-tail | Utility |
| N | 158214 | 60459 | 6991 |
| ($lb_f$) | (35568) | (13 592) | (1 572) |
| $m^2$ | 143.18 | 98.15 | 31.78 |
| ($ft^2$) | (1541.18) | (1056.48) | (342.08) |

Table 5: $T$ and $S$ calculated from the constrain diagram.

#### 4.2.4 Aircraft Competition

In this subsection, it's presented a comparison between our configuration and other aircraft configurations that have the same type of main drivers. In this section these main drivers are the PAX, the cruise Mach Number and the range. The structural factors of the other configuration are very similar to the ones chosen for the concepts, leading the author to say they are conservative. The $W/S$ are significantly lower in the Box-wing and in the V-tail, for the Utility is at the same level of two thirds of the competition presented.

#### 4.2.5 Airfoil and Wing/Tail Selection & Geometry Sizing

In this section are presented the main decisions made in the exterior aspect of the aircraft. Wings, tails and fuselages will be described.

In the wings will be decided the airfoil and wing geometry. For the Box-wing will be presented the method used to calculate the geometry of the two wings.

Taking in account the cruise speed, the kind of flow desired, the mission and the quantity of fuel wanted, in the wings, it was decided to use the airfoils presented in table 6.

| | Aircraft | | |
|---|---|---|---|
| | Box-wing | V-tail | Utility |
| Airfoil | SC(2) - 0410 | | NACA 64 A415 |
| $t/c$ | 10% | 10% | 15% |
| $C_{L_{Design}}$ | 0.4 | 0.4 | 0.4 |

Table 6: Airfoils selected for the wings.

The values for the wings of the V-tail and Utility are presented in table 7.

| | | Aircraft | |
|---|---|---|---|
| | | V-tail | Utility |
| Vertical Location (VL) | | Low | High |
| $S$ | $m^2$ | 98.15 | 31.78 |
| Aspect Ratio($AR$) | | 10.5 | 8 |
| Taper Ratio (TR) | | 0.3 | 0.4 |
| Wingspan ($b$) | m | 32.1 | 15.9 |
| Root Chord ($c_{root}$) | m | 4.7 | 2.9 |
| Tip Chord ($c_{tip}$) | m | 1.4 | 1.1 |
| Swept Angle ($\Lambda$) | deg | 35° | 10° |
| Dihedral Angle ($\Gamma$) | deg | 5° | -2° |

Table 7: V-tail and Utility wing geometry data.

The calculation of the front and rear wings of the Box-wing are done using the method presented in [6]. The calculation of both wings are made in order to maintain the same span and total wing area and still making possible an higher value for the $AR$. This calculation creates two equal wings, if the division is done in half, with the double $AR$ of the reference wing. In our case it was used a front wing with 52.5% of the total area, because by stability reasons is important to have greater lift in the front wing that in the rear wing [6, subsection 5.1.2]. In table 8 the data for the reference wing, forward wing and rearward wing are presented.

| | | Box-wing wings | | |
|---|---|---|---|---|
| | | Reference | Forward | Rearward |
| VL | | Low | High | Low |
| $S$ | $m^2$ | 143.18 | 75.17 | 68.01 |
| $AR$ | | 8 | 15.24 | 16.84 |
| TR | | 0.4 | 0.40 | 0.44 |
| $b$ | m | 33.8 | 33.8 | 33.8 |
| $c_{root}$ | m | 6.0 | 3.2 | 2.9 |
| $c_{tip}$ | m | 2.4 | 1.3 | 1.3 |
| $\Lambda$ | deg | 30° | 30° | -28° |
| $\Gamma$ | deg | 5° | -2° | 3° |

Table 8: Box-wing geometry data.

The criteria used to select the tail airfoil are based in the cruise speed, the laminar criteria applied in the wings and in the fact that the tail airfoil must have a lower $t/c$ than the actual wing airfoil. In table 9 are presented the airfoils and their $t/c$.

| | Aircraft | | | |
|---|---|---|---|---|
| | Box-wing | V-tail | Utility | |
| | VT | V-tail | VT | HT |
| Airfoil | SC(2) - 0008 | | NACA 66-010 | |
| $t/c$ | 8% | 8% | 10% | 10% |

Table 9: Airfoils selected for the tails.

In table ?? are presented the dimensions and parameters of the different aircraft tails.

Most of the decisions of the fuselage were made by the design team, which decided the length and sections of the fuselages. Most decisions were made in order to obtain the desired commercial position.

The dimensions of the aircraft fuselage are presented in table 11.

| | | Aircraft | | |
|---|---|---|---|---|
| | | Box-wing | V-tail | Utility |
| Length | m | 41.7 | 29.2 | 7.6 |
| Max diameter | m | 4.5 | 3.1 | 2.2 |

Table 11: Principal dimensions of the aircraft fuselages.

#### 4.2.6 Configuration layout

Most of this work was developed, by the design team, in order to reserve space, in the configuration, for the eventual equipments, passengers and cargo. In this subsection there are presented the "boxes" reserved for those equipments,as well as, passengers and cargo arrangements. The EMBRAER team made a brief security and certification assessment in all configurations.

| | | Aircraft | | | |
|---|---|---|---|---|---|
| | | Box-Wing | V-tail | Utility | |
| | | Vertical tail | V-tail | Vertical tail | Horizontal tail |
| $S$ | $m^2$ | 20.39 | 2 * 20.2 | 2 * 1.56 | 7.48 |
| V-tail angle | deg | - | 42.87° | - | - |
| Aspect Ratio | | 1.5 | 5 | 2.0 | 4.5 |
| Taper Ratio | | 0.5 | 0.4 | 1 | 1 |
| Wingspan | m | 5.5 | 5.5 | 1.77 | 5.80 |
| Root Chord | m | 4.9 | 5.47 | 0.88 | 1.29 |
| Tip Chord | m | 2.5 | 2.19 | 0.88 | 1.29 |
| Swept Angle | deg | 40° | 40° | 15° | 0° |
| $C_{vt}$ | | .09 * .9 | 0.9 * 0.85 * 0.9 - 1 * 0.85 * 0.9 | 0.04 | 0.70 |
| $L_{vt}$ | m | 19.3 | 11.6 | 6.5 | 6.5 |
| $c_{rudder}/c_{\text{VT}}$ | | 0.32 | 0.32 | 0.4 | 0.45 |

Table 10: Box-wing tail geometry data.

#### 4.2.7 Special Considerations in Configuration Layout

In this subsection, are be presented some special considerations that were taken during the design process. These are, as referred in [5], "the intangible considerations that the designer should do when making the initial layout. These include aerodynamics, structures, (...), producibility, and maintenance."

It were verified if the after fuselage angle are in the intervals advised in [5, page 217], for the Utility this angle is higher than the advised, but the after door wanted, by the design team, limited the after fuselage angle. It was also considered the supersonic area rule in the design of the V-tail fuselage, but greater effort should have been given to this matter, in the opinion of the author.

#### 4.2.8 Engine definition

To define the engines for the Box-wing were chosen two reference engines presented in two different papers. The UHB was based in [3] and the CROR was based in [4]. The scaled engines are presented in table

| | | UHB | Open-Rotor |
|---|---|---|---|
| $\text{Thrust}_{SLS}$ | kN | 118.7 | 118.7 |
| BPR | | 14.7 | N.A. |
| Weight | kg | 3476 | 4077 |
| Nacelle diameter | m | 2.3 | 1.7 |
| Fan/Propeller diameter | m | 2.0 | 4.2 |
| $\text{TSFC}_{SLS}$ | mg/Ns | 7.278 | 4.474 |
| $\text{TSFC}_{cruise}$ | mg/Ns | 14.216 | 12.120 |

Table 12: Scaled Box-wing engines.

For the definition of the V-tail and Utility engines was used an first-order statistical model for nonafterburning engines [5, equation 10.4-10.9]. To account next-generation engines a reduction of 20% in the TSFC, weight and length applied to the engines.

| | | VT-NX | UT-NX |
|---|---|---|---|
| $\text{Thrust}_{SLS}$ | kN | 45.35 | 9.1 |
| BPR | | 6 | 4 |
| Weight | kg | 596 | 103 |
| Diameter | m | 1.3 | 0.5 |
| $\text{TSFC}_{SLS}$ | mg/Ns | 7.399 | 9.406 |
| $\text{TSFC}_{cruise}$ | mg/Ns | 14.816 | 16.375 |

Table 13: Scaled Box-wing engines.

For the Utility are considered more one electric generator and two electric motors, for the lift-fans. In table 14 are presented the power supplied (PS) by each, the specific power density (SPD) considered, and the weight (W) of this components.

| | | Motor-NX | Generator-NX |
|---|---|---|---|
| PS | kW | 355.3 | 191.8 |
| SPD | kW/kg | 7.1 | 7.1 |
| W | kg | 50 | 27 |

Table 14: Next generation electric engines/generators defined for the Utility.

From the calculations of the MTOW, we get the first estimation of the fuel needed for each mission. In table 15, it's presented the fuel weight and necessary reservoir dimensions. It was considered that the fuel is Jet A-1, the least dense fuel used in commercial jet aircraft. This fuel has a density of 0.804 kg/L.

For the Utility there is another power source that is important to account, the batteries. To allow the use of the motors, for 30 minutes, is necessary a 203

| | | Aircraft | | |
|---|---|---|---|---|
| | | Box-wing | V-tail | Utility |
| Fuel weight | kg | 14324.5 | 8946.5 | 425.3 |
| Tank vol. | $m^3$ | 17.82 | 11.13 | 0.53 |

Table 15: Fuel weight and reservoir volume.

kg battery of Li-$O_2$.

#### 4.2.9 Landing Gear and Subsystems

In this subsection, it will be presented the landing gear used in each configuration, with the detailing of arrangement, position and tire sizing. It's also presented an brief description of the other subsystems used in these configurations.

The Box-wing, the V-tail and the Utility have an tricycle arrangement for the landing gear. The first sizing of the tires was done using the methodology described in reference [5, table 11.1]. In table 16 are presented wheels dimensions resulting from this method, for each aircraft configuration.

| | | Aircraft | | |
|---|---|---|---|---|
| | | Box-wing | V-tail | Utility |
| Diameter | cm | 107.1 | 74.6 | 66.2 |
| Width | cm | 38.1 | 23.2 | 23.4 |

Table 16: Landing gear tires dimensions.

There's a big tendency in change big part of the subsystems to more electric equipments, like electric deicing, control surfaces, brakes, among others. The transference of these systems to electric systems, imposes a greater electric capability to the aircraft, but since the efficiency of the electric systems are very high, benefits in weight and in total efficiency can be obtained. For that the two configurations that have have APUs, the Box-wing and the V-tail, are designed with more electric capability than todays aircraft. In table 17 is presented the power rating of the two configurations.

| | | Aircraft | |
|---|---|---|---|
| | | Box-wing | V-tail |
| Power rating | kVA | 180 | 90 |

Table 17: Box-wing and V-tail electric systems.

### 4.3. Revised Layout

In this section the main decisions presented in the subsection 4.2 are study in more depth. By applying simple methods is possible to detail the aircraft more and create more solid concepts.

#### 4.3.1 Aerodynamics

In this subsection is presented the study done to the airfoils and the lifting surfaces. First are studied the airfoils of the wings and empennages, followed by the study of the 3D surfaces. In table 18 are presented the characteristics of the airfoils studied.

From figure 3 to 6 are presented the 3D lift slope in function of the Mach number.

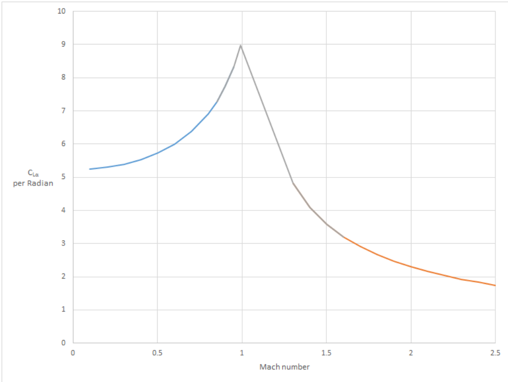


Figure 3: Lift-curve slope vs Mach number for the V-tail 3D wing.

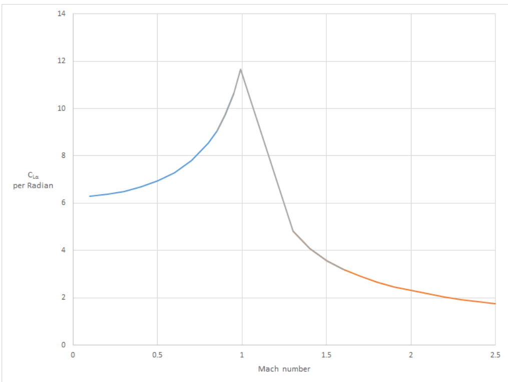


Figure 4: Lift-curve slope vs Mach number for the Box-wing forward 3D wing.

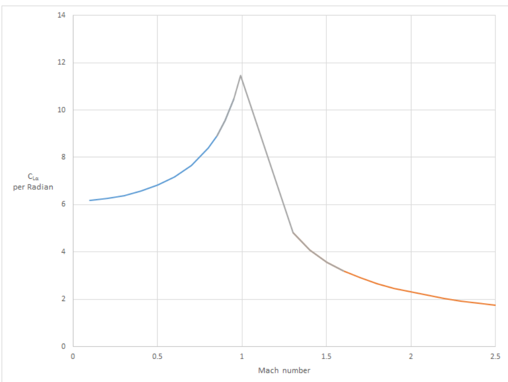


Figure 5: Lift-curve slope vs Mach number for the Box-wing afterward 3D wing.

| Aircraft | | $C_l$ vs $\alpha$ | Max. Lift | | Lift over Drag | | $C_{d_{\min}}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | $C_{l_{\max}}$ | $\alpha$ (deg) | $L/D$ | $\alpha$ (deg) | $C_d$ | $\alpha$ (deg) | $C_l$ |
| BX | For. wing | $C_l = 0.182\alpha + 0.422$ | 1.988 | 11° | 116.98 | 8° | 0.012 | -4° | -0.33 |
| | Aft. wing | $C_l = 0.182\alpha + 0.423$ | 1.988 | 11° | 115.65 | 8° | 0.012 | -4° | -0.33 |
| | V. Tail | $C_l = 0.177\alpha + 0.000$ | 1.553 | 11° | 145.44 | 9° | .008 | 0° | 0 |
| V-tail | Wing | $C_l = 0.250\alpha + 0.581$ | 2.737 | 11° | 163.77 | 8° | 0.012 | -5° | -0.72 |
| | Tail | $C_l = 0.243\alpha + 0.000$ | 2.138 | 11° | 197.57 | 9° | 0.008 | 0° | 0 |
| Utility | Wing | $C_l = 0.127\alpha + 0.431$ | 1.636 | 12° | 137.08 | 5° | 0.005 | 0° | 0.44 |
| | V. tail | $C_l = 0.106\alpha + 0.000$ | 0.854 | 8° | 86.69 | 8° | 0.004 | 0° | 0 |
| | H. Tail | $C_l = 0.111\alpha + 0.000$ | 0.882 | 9° | 92.60 | 9° | 0.004 | 0° | 0 |

Table 18: Airfoil characteristics for the configurations at cruise speed.

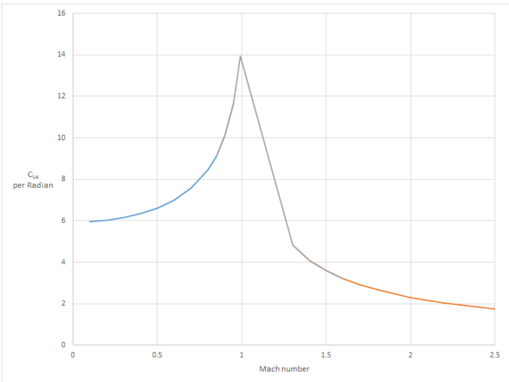


Figure 6: Lift-curve slope vs Mach number for the Utility 3D wing.

The aircraft drag can be divided in two main components, the parasite drag and the "drag due to lift". The parasite drag for the cruise speed of the configurations is presented in table 19. For transonic and supersonic speeds the wave drag is also accounted to the parasite drag. The values of the wave drag ($C_{D_{\text{wave}}}$), at Mach = 1.2, $M_{\text{DD}}$ and $M_{\text{cr}}$ are also presented in table 19.

| | Aircraft | | |
|---|---|---|---|
| | Box-wing | V-tail | Utility |
| $(C_{D_0})_{\text{subsonic}}$ | 0.014 | 0.010 | 0.031 |
| $C_{D_{\text{wave}}}$ | 0.227 | 0.037 | 0.373 |
| $M_{\text{DD}}$ | 0.82 | 0.85 | 0.73 |
| $M_{\text{cr}}$ | 0.74 | 0.77 | 0.65 |

Table 19: Parasite drag.

The "drag-due-to-lift factor" and the Oswald efficiency factor are presented in table 20.

### 4.3.2 Propulsion

In this section is presented the part-power study of the engines at the configurations cruise speed and at Mach 0.2. This is presented in figure 7. I's also presented a comparison between the fuel burned by the different engines in the Box-wing, in table 21.

| | Aircraft | | | |
|---|---|---|---|---|
| | Box-wing | | V-tail | Utility |
| | Oswald | Calculated | | |
| $e$ | 0.9276 | 0.5091 | 0.2465 | 0.6900 |
| $k$ | 0.0403 | 0.0734 | 0.1025 | 0.0481 |

Table 20: Calculated $e$ and $k$ for the three configurations.

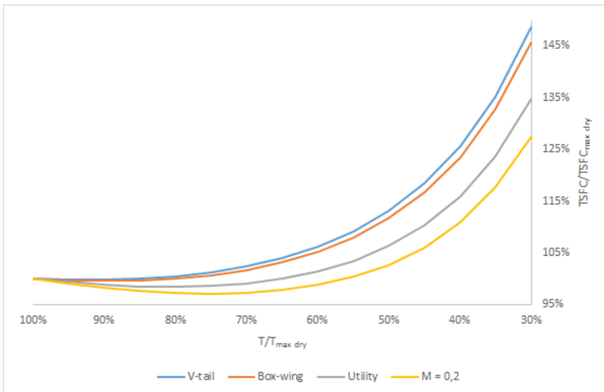


Figure 7: Part Power Operation for the three concepts cruise speed and for Mach = 0.2.

| | | Box-wing | | |
|---|---|---|---|---|
| | | Ref. | UHB | CROR |
| Block fuel | kg | 14324 | 14318 | 12311 |
| Weight difference | kg | 0 | 7 | 2014 |
| Reduction in % | % | N.A. | 0.048 | 14.056 |

Table 21: Comparison between the block fuel of the different engines of the Box-wing.

### 4.3.3 Weights

In this section is calculated the weight of each component of the aircraft

In table 22 are presented the MTOW calculated by this method for all configurations, along with the aircraft center of gravity (c.g.) with full load of fuel and no fuel.

| | | Aircraft | | | |
|---|---|---|---|---|---|
| | | Box-wing (BW) turbofan | Box-wing CROR | V-tail (V-T) | Utility (UT) |
| MTOW | kg | 63682 | 61675 | 26895 | 3469 |
| | | Full fuel | | | |
| $x_{c.g.}/L_{fuselage}$ | | 0.444 | 0.443 | 0.544 | 0.600 |
| $x_{c.g.}$ | m | 18.33 | 18.32 | 15.89 | 4.54 |
| | | No fuel | | | |
| $x_{c.g.}/L_{fuselage}$ | | 0.448 | 0.447 | 0.556 | 0.596 |
| $x_{c.g.}$ | m | 18.52 | 18.49 | 16.24 | 4.51 |

Table 22: Aircraft c.g. position with full fuel and no fuel.

#### 4.3.4 Static Stability

In this section is presented the longitudinal (pitch) stability, characterized by the coefficient of longitudinal stability ($C_{M_\alpha}$) and static margin (SM),in table 23 , and the longitudinal and directional stability, characterized by the lateral stability coefficient ($C_{L_\beta}$) and the coefficient of directional stability ($C_{n_\beta}$), in table 24.

| | Aircraft | | | |
|---|---|---|---|---|
| | BW UHB | BW CROR | V-T | UT |
| | Full fuel | | | |
| $C_{M_\alpha}$ | -0.659 | -0.712 | -1.489 | -1.377 |
| SM | 8.2 | 8.8 | 17.7 | 19.5 |
| | No fuel | | | |
| $C_{m_\alpha}$ | -0.001 | -0.084 | -0.675 | -1.468 |
| SM | 0.0 | 1.0 | 8.0 | 20.8 |

Table 23: Configurations $C_{m_\alpha}$, in Rad$^-1$, and SM, in %.

| | | Aircraft | | |
|---|---|---|---|---|
| | | Box-wing | V-tail | Utility |
| | | Full fuel | | |
| $C_{n_\beta}$ | Rad$^-1$ | 0.242 | 0.302 | 0.121 |
| $C_{L_\beta}$ | Rad$^-1$ | -0.242 | -0.302 | -0.121 |

Table 24: Configurations $C_{n_\beta}$ and $C_{L_\beta}$.

#### 4.3.5 Cost Analysis

In this section is calculated the aircraft cost in function of the number of units produced. For that is used a statistical based model, in which it's possible to calculate the the cost of development from several parameters. The method used is the RAND DAPCA IV Model, developed RAND corporation. In table 25 are presented the cost, per unit of the aircraft developed, in function of the number of units build.

The cost estimated for the first three configurations are very similar to the cost of similar aircraft.

| | Built units in five yeas | | | | |
|---|---|---|---|---|---|
| | 100 | 500 | 1000 | 2000 | 3000 |
| BW UHB | 215.4 | 122.8 | 104.3 | 91.8 | 86.4 |
| BW CROR | 220.0 | 124.8 | 105.8 | 92.9 | 87.3 |
| V-tail | 97.9 | 54.1 | 45.3 | 39.4 | 36.8 |
| Utility | 19.2 | 13.2 | 12.0 | 11.2 | 10.8 |

Table 25: Aircraft unit price in millions of dollars.

The Utility cost, on the other hand, has a much higher cost, leading the author to think that this method it's overshooting the cost. In [5] is referred that people that applied this method to general aviation claim that the costs are reasonably after dividing by four.

## 5. Conclusions

Motivated by the opportunity to participate in an awarded consortium[1], and develop their vision of the future aircraft, was with great enthusiasm that the author worked in this project.

The worked developed was a result of a contract between IDMEC and Alma Design, in which was required the development of the aircraft concepts of project NewFace. That was the work presented in this thesis.

### 5.1. Achivements

Over the course of this thesis became clear that to achieve the maximum eco-efficiency it's necessary to get the "help" of every departments responsible for the aircraft design. The improvements, in aerodynamic, propulsion, structures, materials, systems, and all the other departments, have to be implemented all together, in order to achieve the "greener" aircraft possible, with a good eco-efficiency.

### 5.2. Lessons Learned

For the development of future eco-efficient aircraft based on an integrated design process, the organiza-

[1]This consortium was awarded with the Cristal Cabin Award in 2012 with the project LIFE - Lighter, Integrated, Friendly and Eco-efficient Aircraft Cabin .

tion of the project should have been made with an aerospace design partner either at Embraer or Alma Design. This partner would assist in the definition of the trade studies that would have been useful in the decisions of some of initial parameters, like the cruise speed.

For the Box-wing the main conclusions can be divided in two sections, the LL from aerodynamics and the LL from the propulsion system. Comparing the value of the parasite drag of this concept with the value presented in [?], for the AIRBUS A320, this configurations has a reduction of 36%. This reduction is mainly obtained from the boundary layer control systems considered and the lower MAC of the wings of the Box-wing configuration. The other benefit that would be expectable in the Box-wing is a big reduction of the lift induced drag. Comparing the value obtained using the Oswald value for the reference wing with the value presented in [?] the reduction is only of 6%. This small reduction is a direct consequence of the low vertical distance between the two wings. In the propulsion system is important to refer that with the CROR is possible to achieve a reduction of the fuel burned in the order of 14% comparing with an UHB, despite the higher weight of the CROR.

For the V-tail configuration is important to refer that the parasite drag is lower than usual, on the order of value of a sailplane. This reduction is a resultant of the implementation of HLFC system, allowing for a more laminar aircraft. Other LL was the importance of new composite construction methods that allow for the manufacture of variable section fuselages that have a lower wave drag at high transonic speeds.

In the Utility the main LL were the influence that a back door can have in the parasite drag, it almost doubles, and the fact that the lift-fans have the most effect at lower speeds, at higher speed the aerodynamic lift overshadows the lift-fans effect.

### 5.3. Future Work

There are several possibilities of further work that can be developed to continue the ideas that were opened by the work developed in this thesis. The list presented below features only the suggestions considered most relevant by the author.

The suggestions for future researches are:

- Analyze the risk of the implementation of the technologies, with the assessment of the importance of these technologies for the objectives and improvements of the concepts.
- Perform a aerodynamic analysis with a panel method code or other inviscid code, for the three concepts aircraft and for the wing of the Utility alone.


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