Development of Life Cycle Models for Evaluating Novel Aircraft Configurations

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Thesis to obtain the Master of Science Degree in Aerospace Engineering

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Dedicated to my grandmother Maria Bernardette Portugal
Acknowledgments

This thesis is the final task to obtain the Master of Science degree in Aerospace Engineering at Instituto Superior Técnico, Lisbon University, Portugal. All the research behind this thesis is done according to the knowledge received in the courses that form the Masters Program in Aeronautics. I chose this program two years ago due to the passion I have related to structural mechanics, aerospace structures, aerospace design, laminated composite materials, mechanical behaviour of materials and project management. In the first years of my bachelor degree I also had some courses that gave me the important background to fulfil my gap in the avionics domain, such as electronics, digital systems and flight control. Although these courses did not have direct application in this thesis, they had their part in the development of my global aerospace knowledge. This Integrated Masters is a synthesis of the advanced technologies that continue to grow in the present to solve the future goals. Those technologies are the main boosters of the development of the various types of flying vehicles such as airplanes, helicopters, rockets and satellites. This Masters Program enables the Aerospace Engineer to intervene in all phases of the life cycle of a vehicle, starting by its design, passing through its construction and commissioning (testing and manufacturing) and also its operation, maintenance and final disposal. Therefore, I would like to congratulate the creators of this Integrated Masters that, by joining the important backgrounds of Mechanical Engineering and Electrotechnical Engineering, launched the first in Aerospace Engineering program in Portugal in 1992.

First of all, I would like to thank my supervisor prof. Fernando Lau. In my first year at Instituto Superior Técnico I was not in this Integrated Masters Program. I started by studying Mechanical Engineering and at the end of the first year I decided to change my path to Aerospace Engineering, so I went to his office to understand what this program had to offer. That conversation we had was crucial to my change of academic course. Also, he taught me a lot of mechanical background in many courses such that he motivated me a lot to do my Masters Program in the Aeronautics area. I would like to thank also to my other supervisor prof. Inês Ribeiro that gave me the motivation to work with Life Cycle Models. In her course of project management the lectures of process-based cost models were the ones that made me advance to this thesis. In the actual society, it is critical to an engineer to have the theoretical and practical background of cost models. Without it, the projects will fail in financial terms. Dr. Frederico Afonso taught me aero-elasticity in the aerospace structures course as well as structural analysis and optimization of the aircraft components and these knowledges were decisive for the thesis development. I would like to thank to professor Domenico Lahaye from T. U. Delft who I met in the ATHENS program and showed availability to help me in my project.

The last five years at this university were great also due to the friends I made. They were very important to my growth as a student, as a friend and as a human. The same difficulties we had in our journey made us grow stronger both individually and as a group of students, friends and humans.
Finally, the home support I had from my family was very important along the Masters Program but mostly during the thesis development. I would like to thank my parents and my sister that always kept the faith in my work and in my capacities. Thank you all!
Resumo

A evolução da economia e da população nos últimos anos, sobretudo nos países em desenvolvimento, tem levado ao crescimento contínuo e à expansão da indústria aeronáutica, conduzindo a uma necessidade de incrementação da produção de aeronaves não só em termos de quantidade, mas também de modelos, tais como os de asa alongada, e de novos materiais como os compósitos. Apesar de o alumínio ser, actualmente, o material mais utilizado na indústria aeronáutica, os compósitos começam a ganhar a sua posição no mercado da aviação devido às suas excelentes propriedades mecânicas que acentuam na perfeição nos requerimentos desta indústria.

O objectivo principal desta tese é desenvolver uma análise multidisciplinar de variações discretas de um modelo simplificado, fornecido pela empresa brasileira EMBRAER no projecto NOVEMOR, para determinar qual o melhor modelo de asa para as 12 configurações consideradas. Para tal, foram feitas variações em termos de geometria interna e externa e a nível de material. Os vários modelos de asas foram analisados em termos de desempenho aerodinâmico, comportamento estrutural e análise de ciclo de vida em termos ambientais e financeiros nas fases de produção, uso e fim de vida.

Os resultados finais foram fornecidos pela análise multidisciplinar e a comparação entre os diferentes modelos de asa foi feita através de um Processo Analítico de Hierarquias. A fonte principal de custo foi determinada e foram desenvolvidos estudos paramétricos para clarificar as conclusões desta análise multidisciplinar.

Abstract

The economy’s and population’s growths in the last years, specially in the developing countries, have been conducing to an increment of the demand for aircraft not only in terms of quantity but also in terms of configuration such as the high aspect ratio ones and new materials such as the composites. Although aluminium is currently the most used material in aeronautics, composites start to enter the aviation market due to their great mechanical properties that fulfill in a better way this industry requirements.

The main objective of this thesis is to perform a multidisciplinary analysis of discrete variations in a simplified wing model, provided by the Brazilian company EMBRAER on project NOVEMOR, in order to obtain the best wing model out of 12 different configurations. Variations in the internal and external geometries and material were performed. The different wing configurations were analysed regarding their aerodynamic performance, structural behaviour and life cycle impacts both in environmental and financial terms for the production, use and End-of-Life phases.

The final results were provided by the multidisciplinary analysis and the comparison between all the wing configurations was made by the use of an Analytical Hierarchy Process. Furthermore, the main cost source was determined and parametric studies were performed in order to get clearer conclusions from this multidisciplinary analysis.

Keywords: High Aspect Ratio Wing, Composite, Aluminium, Multidisciplinary Analysis, Life Cycle Analysis.
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Nomenclature

Greek symbols

\(\alpha\)  Angle of Attack.

\(\beta\)  Compressibility Factor.

\(\lambda\)  Tapper Ratio.

\(\Lambda_{\text{break}}\)  Sweep Angle on the Wing's Break.

\(\Lambda_{\text{LE}}\)  Sweep Angle of the Leading Edge.

\(\Lambda_{\text{root}}\)  Sweep Angle on the Wing's Root.

\(\left(\Delta \frac{L}{D}\right)_{\%}\)  Percentage of Lift over Drag increase.

\(\nu\)  Air Viscosity Coefficient.

\(\nu_{\text{Al}}\)  Aluminium’s Poisson Coefficient.

\(\rho_{\text{Al}}\)  Aluminium’s Density.

\(\rho_{\text{cr}}\)  Air Density at Cruise Altitude.

\(\rho_{\text{mat}}\)  Material’s Density.

\(\sigma_{\text{max}}\)  Maximum Stress.

\(\sigma_{y,\text{Al}}\)  Aluminium’s Yield Stress.

Roman symbols

\(\%\text{Allocation}\)  Percentage of Allocation for a certain part.

\(a_{\text{c}}\)  Working Engagement.

\(a_{\text{p}}\)  Cut’s Depth.

\(AFP_{\text{lay-up rate}}\)  AFP lay-up rate.

\(AR\)  Aspect Ratio.

\(\text{Area}_{\text{req}}\)  Area required for the machines, in \(m^2\).
Areal Weight, in kg/m$^2$.

ATL lay-up rate. ATL lay-up rate.

AVR Area or Volume Removed.

$b$ Total Wing Span (Tip-to-Tip).

Breaks paid Paid Breaks of the Workers, in hours.

Breaks unpaid Unpaid Breaks of the Workers, in hours.

$\tau$ Mean Wing Chord.

c Wing Chord.

$C_D$ Drag Coefficient for the main wing.

$C_f$ Viscous Drag Coefficient.

$C_L$ Lift Coefficient for the main wing.

$C_M$ Moment Coefficient for the main wing.

c$_r$ Wing Chord at the Root.

c$_t$ Wing Chord at the Tip.

c$\text{break}$ Wing Chord at the Break.

$C_{D0}$ Wing Base Drag Coefficient.

$C_{D\text{wing}1}$ Wing Drag Coefficient of the Original Wing.

$C_{D\text{wing}2}$ Wing Drag Coefficient of the High AR Wing.

$C_{L\alpha}$ Lift Curve Slope.

$C_{L\alpha=0}$ Lift Coefficient for Zero Angle of Attack.

$C_{L\alpha\text{original}}$ Lift Curve Slope of the Original Wing.

$C_{L\alpha\text{high}}$ Lift Curve Slope of the High AR Wing.

$C_{L\text{wing}1}$ Lift Coefficient of the Original Wing.

$C_{L\text{wing}2}$ Lift Coefficient of the High AR Wing.

$C_{TSFC}$ Thrust-Specific Fuel Consumption.

$C_{D0\text{wing}1}$ Wing Base Drag Coefficient of the Original Wing.

$C_{D0\text{wing}2}$ Wing Base Drag Coefficient of the High AR Wing.

Consumables$_{\text{cost/unit}}$ Cost of a Unit of Consumables, in euros/unit.
Cost\textsubscript{acquisition} Cost of a single Machine/Tool, in €/unit.

Cost\textsubscript{Building} Total Investment in Building, in €.

Cost\textsubscript{construction} Building’s Construction expenses, in €.

Cost\textsubscript{consumables/sqm} Consumables cost per square meter, in €/m\textsuperscript{2}.

Cost\textsubscript{consumables} Consumables cost, in €.

Cost\textsubscript{euro/kg} Material cost in €/kg.

Cost\textsubscript{euro/sqm} Material cost in €/m\textsuperscript{2}.

Cost\textsubscript{Machine} Cost of all the Machines bought, in €.

Cost\textsubscript{Maintenance} Maintenance Cost, in €.

Cost\textsubscript{Overhead} Indirect Costs to the production, in €.

Cost\textsubscript{rework\_material} Cost related to the material rework, in €.

Cost\textsubscript{scrap\_kg} Scrap cost for the composite models, in €/kg.

Cost\textsubscript{scrap\_metal} Scrap cost for the metal models, in €.

Cost\textsubscript{scrap} Scrap cost for the composite models, in €.

Cost\textsubscript{Tool} Cost of all the Tools bought, in €.

CT Cycle Time.

%\textsubscript{dedication} Workers’ dedication, in percentage, to perform a certain task.

D\textsubscript{cap} Cutting Diameter at actual Depth of Cut.

Downtime Time non-dedicated to the parts’ production.

DpY Days per Year in which the company is dedicated to the production.

%\textsubscript{eff} Percentage of Efficiency.

\(e\) Oswald Efficiency.

E\textsubscript{Al} Aluminium’s Young Modulus.

Energy\textsubscript{cost} Energy Cost.

f\textsubscript{z} Feed per Tooth.

FC\textsubscript{High\_AR} Fuel Consumption on a single flight by an aircraft with the high \textit{AR} wing configuration, in kg.

FC\textsubscript{original} Fuel Consumption on a single flight by an aircraft with the original \textit{AR} wing configuration, in kg.
**Fixed Cost**

**G\(_{Al}\)** Aluminium’s Shear Modulus.

**h\(_{cr}\)** Cruise Altitude.

**h\(_{layer}\)** Layer’s Thickness.

**\(\%_{IdleSpace}\)** Percentage of Space that should be dedicated to the production but is wasted by negligence.

**I\(_i\)** Initial Investment \(i\).

**Idle** Time that the workers should dedicate to the production but is wasted by negligence.

**JIG\(_{setup}\)** Holding tools’ set-up.

**JIG\(_{totalTime}\)** Holding tools’ total time of operation.

**\(L\)** Lift to Drag ratio

**\(\left(\frac{L}{D}\right)_{highAR}\)** Lift to Drag ratio for the high \(AR\) wing

**\(\left(\frac{L}{D}\right)_{original}\)** Lift to Drag ratio for the original wing

**L\(_1\)** Root to Break length

**L\(_2\)** Break to Tip length

**Labour\(_{cost}\)** Labour Cost.

**\(\%_{Maintenance}\)** Percentage of Maintenance required for a certain machine.

**\(\%_{Overhead}\)** Percentage of Overhead in the model.

**M\(_{cr}\)** Cruise Mach Number.

**M\(_{eff}\)** Effective Mach Number.

**Maintenance\(_{OnShift}\)** On Shift Maintenance, in hours.

**Mat\(_{area}\)** Material area in \(m^2\).

**Mat\(_{cost}(aluminium)\)** Cost of the aluminium parts, in euros.

**Mat\(_{cost}(block_fibreplace)\)** Material cost in the fibre placement block, in euros.

**Mat\(_{cost}(carbon_f)\)** Cost of the carbon fibre material, in euros.

**Mat\(_{cost}(copper + glass_f)\)** Cost of the copper and glass fibre material, in euros.

**Material\(_{req_rework}\)** Percentage of material required for the reworking process.

**MRR** Material Removal Rate.

**n** Spindle Speed.
$n_j$ Life of the Product $j$.

$n_{consumables}$ Number of consumables used.

$n_{layers}$ Number of layers.

$n_{machine}$ Number of Machines bought.

$n_{parts}$ Number of parts produced.

$n_{stages}$ Number of Stages in moulding.

$n_{tool}$ Number of Tools bought.

$n_{workers}$ Number of workers necessary to do the task.

$\%_{\text{passes}}$ Percentage of the total parts that are in a good condition to go to the next stage of the process.

$P_c$ Cutting Perimeter.

$P_{consumption}$ Power Consumption in kW.

$Part_{area}$ Part area, in m$^2$.

$Part_{height}$ Part Height, in m.

$Part_{volume}$ Part Volume, in m$^3$.

$\%_{\text{quality\ scrap}}$ Percentage quality scrap.

$Q_w$ Interference Factor for the Main Wing.

$\%_{\text{rework\ passes}}$ Percentage of the total parts that are in a good condition to go to rework in the blocks.

$\%_{\text{rework}}$ Percentage of the total material that is reworked in the blocks.

$\%_{\text{rework\ scrap}}$ Percentage reworked scrap.

$R$ Range.

$r$ Opportunity Cost of Capital.

$rate_{lay-up}$ Lay-up Rate.

$Re_{cr}$ Reynolds Number at Cruise Conditions.

$Re_{cr\ wing\ 1}$ Reynolds Number at Cruise Conditions for the Original Wing.

$Re_{cr\ wing\ 2}$ Reynolds Number at Cruise Conditions for the High AR Wing.

$RM_{volume}$ Raw Material Volume, in m$^3$.

$\frac{S_{\text{wet}}}{S}$ Wetted Wing Area over Wing Planform Area.

$S$ Total Wing Area (both wings).
Maximum Thickness over Chord Ratio.

\( \frac{1}{\epsilon} \) max

Percentage of technical scrap.

\( \%\text{tecnical\_scrap} \)

Aluminium Layer's Thickness.

\( t_{\text{al}} \)

Available Time, in hours.

\( T_{\text{available}} \)

Composite Layer’s Thickness.

\( t_{\text{comp}} \)

Corrected Layer Time, after the efficiency effect, in hours.

\( T_{\text{layer\_correct}} \)

Layer Time, in hours.

\( T_{\text{layer}} \)

Machine Time for demolding and finishing macro block, in hours.

\( T_{\text{machine\_demold}} \)

Time required to do the work \( i \), in hours.

\( T_{\text{req}} \)

Total Beam Thickness.

\( t_{\text{total}} \)

Unit Energy Cost in euros/kWh.

\( \text{Unit\_Energy\_cost} \)

Unplanned Downtime, in hours.

\( \text{Unplanned\_Downtime} \)

Real Time spent on the part’s production.

\( U_{\text{ptime}} \)

Cutting Speed.

\( v_{\text{c}} \)

Table Feed or Feed Speed.

\( v_{\text{f}} \)

Percentage in Volume.

\( V_{\%} \)

Cruise Speed.

\( V_{\text{cr}} \)

Volume of fuel consumed on a single flight by an aircraft with the high AR wing configuration, in L.

\( V_{\text{FC\_high\_AR}} \)

Volume of fuel consumed on a single flight by an aircraft with the original AR wing configuration, in L.

\( V_{\text{FC\_original}} \)

Wing Loading.

\( W_{\\text{S}} \)

Fuel Weight at the end of the cruise phase.

\( W_{f} \)

Fuel Weight at the beginning of the cruise phase.

\( W_{i} \)

Maximum Tip Displacement.

\( w_{\text{max}} \)

Worker’s salary in euros/hour.

\( \text{wage} \)

Carbon Fibre Weight.

\( \text{Weight\_carbon} \)

Raw Material Weight, in kg.

\( \text{Weight\_RM} \)
\( \frac{x}{c} \) \( \frac{z}{c} \) max Chordwise Position of the Maximum Thickness.

\( x_{ac} \) Position of the Aerodynamic Centre.

\( x_{CG} \) Position of the Gravity Centre.

\( z_c \) Number of Effective Teeth.
# Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFP</td>
<td>Automated Fibre Placement</td>
</tr>
<tr>
<td>ATL</td>
<td>Automated Tape Laying</td>
</tr>
<tr>
<td>BWB</td>
<td>Blended Wing Body</td>
</tr>
<tr>
<td>CG</td>
<td>Centre of Gravity</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numeric Control</td>
</tr>
<tr>
<td>CTLM</td>
<td>Contour Tape Laminating Machine</td>
</tr>
<tr>
<td>EOL</td>
<td>End-of-Life</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre Reinforced Plastic</td>
</tr>
<tr>
<td>FW</td>
<td>Filament Winding</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standardization Organization</td>
</tr>
<tr>
<td>JIG</td>
<td>Holding tool used in metal's manufacturing pro-</td>
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<tr>
<td></td>
<td>cesses to support the material</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>LCC</td>
<td>Life Cycle Costs</td>
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<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<td>PBCM</td>
<td>Process Based Cost Models</td>
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<td>PBM</td>
<td>Process Based Model</td>
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<tr>
<td>PREPREG</td>
<td>&quot;pre-impregnated&quot; composite fibres</td>
</tr>
<tr>
<td>RPK</td>
<td>Revenue Passenger Kilometre</td>
</tr>
<tr>
<td>SARS</td>
<td>Severate Acute Respiratory Syndrome</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Aircraft</td>
</tr>
<tr>
<td>WTC</td>
<td>World Trade Centre</td>
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</tbody>
</table>

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Chapter 1

Introduction

A product such as an aircraft component has a technical life cycle that can be given by a S-curve. The product’s life cycle follows the four fixed stages birth, growth, maturity and death, like the living organisms [1]. In the first steps of the development, products suffer an introductory stage in which there are no net profits because the number of units sold is usually very low. In this stage it is important to invest a lot in the products development and optimization, so that the best concept can be generated. Also, in this early stage of the product’s life cycle, the technology’s spread may be limited by the absence of knowledge and tools. A growth step follows this initial one, in which the product reaches a good level of popularity and the number of sales becomes significant. This growth should be high in such a way that it reaches the break-even point as soon as possible, so that the loss ends and the profit due to the product’s sales begin to accumulate. After the growth, the maturity step appears and it is when the profit increases mostly due to the low investment in developing the product’s technology and to the number of sales that continues to raise. To end the product’s life cycle there is the decline step. Current technology in this final stage is not very developed, since it has already reached its heyday. Nowadays, the conventional aircraft designs are in the last step of their S-curve [2]. Therefore, the aerospace engineers are trying to develop new aircraft configurations to meet the market’s needs. In this thesis, a novel wing configuration such as a high aspect ratio (AR) concept will be analysed and compared with regular size configurations.

An important factor that had a huge contribution to the generation of novel aircraft configurations is the environmental concern. Governments imposed regulations to reduce aircraft’s emissions. Due to this issue, the engineers need to develop new aircraft configurations or to improve the actual ones in order to obtain a more efficient concept in terms of fuel consumption and emissions [3]. The optimum concept is the one that can be at the same time competitive, lucrative and less pollutant when compared to the other configurations that currently exist in the market. All the stages in an aircraft life are important and need to be well predicted in order to understand the pros and the cons of an investment on a certain model.
1.1 Motivation

In terms of manufacturing and maintenance most of the aircraft structures are known to be built with applications of fibre-reinforced composites. The structures made in composites allow components to have a significant weight reduction, while keeping a high mechanical resistance. Therefore, it is profitable for the aircraft’s operators and maintenance team [4]. Regarding the wings’ structures, not only the material but also the external shape and the internal composition affect the whole aircraft performance.

1.1.1 Global Market Forecast

The aeronautical industry has not stop growing since it was created. According to the AIRBUS Global Market Forecast, there were over 18,000 passenger aircraft and more than 1,500 freighter aircraft in working order in the year 2015. The world annual traffic in that year was 6.6 trillion RPK (Revenue Passenger Kilometre) and the demand in 2035 is estimated to be 16.0 trillions RPK. This demand is very difficult for airlines to reach with their actual fleet, so they need to order new aircraft to counterbalance the endeavour on older planes. The estimation related to the manufacturers indicates that by the year 2035 they will have a total deliver of 33,710 passenger and 2,110 freight aircraft. The passenger fleet will be more than doubled from 2016 to 2035. According to the AIRBUS Global Market Forecast there will be a total of 33,070 new aircraft deliveries by the year 2035, in a market value of $5.2 trillion. The manufacturers are battling for the biggest percentage of market share. In this total deliveries the largest part corresponds to the single-aisle aircraft in an exact value of 23,530. The twin-aisle aircraft will have a demand of 8,060 and the VLA (Very Large Aircraft) will increase its number in 1,480 unities [5].

According to the local economy, the world can be splitted in regions with a mature economy such as Western Europe, North America and Japan, and the other regions with an emerging economy. The early RPK growth is 5.6% for emerging regions and 3.7% for mature regions. In 2016 the regions with an emerging economy represent 38% of the of aircraft service and world wide passengers. This portion tends to grow every year and is expected to reach 55% in the year 2035. Therefore, the manufacturers and aircraft companies start to invest day-by-day more in the market of countries that belong to emerging economy regions [5].

![Figure 1.1: World annual traffic measured in trillion RPK](5)
In figure 1.1 it is important to notice the stagnation between the World Trade Centre (WTC) attacks in 2001 and the outbreak of the virus SARS (Severe Acute Respiratory Syndrome) in 2003. However, since the WTC attacks until now, the annual travel doubled from 3.25 to 6.5 trillion RPK. During this growth period, the market suffered from some draw-backs, specially in 2003 due to the SARS plague and in 2008 with the financial crisis [5]. It is also important to verify that all the oil crisis since 1970’s were beaten by the world annual traffic, which continues to grow until nowadays. The main factors that most contribute for an annual travel growth like the one shown in figure 1.1 are:

- The growth of the markets in regions with an emerging economy;
- The growth of the world's population;
- The choice of aviation as the first option of travelling for medium and long journeys. Nowadays, aviation starts to enter the business of short journey paths;
- The demand of new aircraft contributes for the replacement of the old and less-efficient ones;
- The demand of VLA due to the expansion of the aviation mega-cities;
- The economic liberalization granted by the governments in regions with an emerging economy such as Latin America, Asia and especially Africa.

Novel aircraft configurations can play a crucial role in terms of fulfilling airlines with more fuel efficient models. The continuous growth of the fuels’ prices needs to be fought not only with the improvement of the existing technologies, but also with the implementation of new ones. However, these unconventional configurations need to be refined in order to prove that they are well founded to be a good economic alternative.

1.2 Novel Aircraft Configurations

In order to understand the need for new aircraft concepts it is important to now the characteristics of conventional aircraft configurations.

1.2.1 Conventional Aircraft Configurations

The so called Conventional Aircraft is a generated concept in which the aircraft has two main wings connected to the fuselage by their roots, a tail with horizontal and vertical stabilizers, usually with two engines fixed to the fuselage or to the wings and a landing gear.

A large percentage of the actual operating aircraft are based on the conventional concept. In figure 1.2(a) is represented the model De Havilland DH. 106 Comet which was the first aircraft with a jet engine in the commercial transport market. The engines have the particularity of being an integrated part of the aircraft’s wing [6]. On the Boeing 367-80 model the engines are placed under the wings as it is shown in figure 1.2(b). With this configuration known as tube-and-wing it was possible to install larger engines.
without the need to restore the entire wing [7]. This concept remained untouched for the last decades, in the commercial airlines, and it is the one that is more linked to the term conventional aircraft [8]. Another example of this configuration is the Airbus A350 presented in figure 1.2(c). As it was referred before, the conventional aircraft configuration can have some variations such as fuselage mounted engines [9]. Bombardier is recognized for using this derivation of the concept, which is very common in regional jets (see figure 1.2(d)).

Conventional aircraft configurations are the most studied ones. However, they might not be the most profitable concepts for airlines. Therefore, other configurations are being analysed in order to develop more fuel efficient aircrafts. These novel aircraft configurations are also known as unconventional aircraft configurations [10].

1.2.2 Unconventional Aircraft Configurations

In order to improve the aircraft's operational and maintenance costs, engineers need to develop novel aircraft concepts that can be either more or less disruptive. Parametric studies were made in the aero-dynamic and in the structural domains in order to provide unique properties to an aircraft component in such a way that the new shape is clearly distinguished when compared to the conventional one, even if it is considered small, such as the inclusion of the canard or the increase of the main wing aspect ratio. Therefore, unconventional aircraft configurations start to appear not only in the military, but also in the commercial market. The canard aircraft is an example of this need. Other concepts were also studied, such as the three-surfaced aircraft, the BWB (Blended Wing Body) aircraft and the Prandtl plane [11].
The canard aircraft is a variation of the conventional configuration but has the horizontal stabilizer in front of the main wing instead of having it placed on the tail, as it can be seen in figure 1.3. This unconventional aircraft shape produces a small lift near the aircraft’s nose (the canard). In this concept there are two surfaces providing lift to the body [10].

Canard configurations decrease the induced drag of the aircraft when compared to the conventional ones, because the canard also provides lift to the aircraft. Thus, it requires a smaller main wing area, allowing the increase of its aspect ratio without increasing its span. The conventional model has the main wing and the horizontal stabilizer after the body’s CG (Centre of Gravity), needing a down force on the horizontal stabilizer in order to compensate the momentum produced by the wing’s lift. Therefore, in the conventional design there is one surface with negative lift. With the canard configuration, the CG is between both surfaces and the two of them have a positive lift at the same time, compensating the momentum around the CG [11]. The differences in the forces diagram of the canard and the conventional concept can be seen in figure 1.3.

![Canard Unconventional Aircraft](image)

Figure 1.3: Canard Unconventional Aircraft

There are other unconventional aircraft concepts studied but they are not so familiar as the Canard configuration. The three-surface aircraft is a coalescence of the conventional configuration with the canard concept. Therefore, this configuration is based on the same principle as the canard aircraft, with a horizontal stabilizer in front of the main wing, but with another one on the tail. The key advantage of this three-surface configuration is to give more flexibility to the aircraft designers while the structural stability is guaranteed. However, this concept is safer when the canard is connected to the bottom part of the fuselage and the tail is in the T-tail configuration. Consequently, the interference between the three lifting surfaces is avoided [10]. An example of this unconventional aircraft is the Piaggio P.180 exhibited in figure 1.4(a).

In 1924 Ludwig Prandtl began his research on the Prandtl-plane model. In his theory he developed a box-wing configuration and the results determined a lifting system with a very low value of induced drag [13]. Hence, this design is considered as the “Best Wing System”. This concept is shown in figure 1.4(b). The principal peculiarity of the Prandtl-plane is the fact that both wings have the same lift distribution and in the vertical wing’s tips there is a butterfly shaped lift distribution. Free vortices induce constant velocities in every span section of the two wings in the condition of minimum induced drag. In
the vertical wing’s tips these induced velocities are null as it is determined in the Munk’s condition for minimum induced drag [14].

In the BWB aircraft, the fuselage and the wings are unified in one single blended body. The fuselage has the shape of an airfoil and because of that design, it produces lift just like the wings. Therefore, the aircraft weight has a more equally distribution along the body and due to this fact the bending moments in the aircraft components are lower. However, in an acrobatic manoeuvre with negative g’s, the lift force will be added to the weight, generating higher moments. In the conventional aircraft, the load applied in the fuselage is orthogonal to the load applied in the wings, introducing a significant bending moment that can be compensated by increasing the structural stiffness. However, the increase of this property produces a raise on the aircraft’s total weight. Updating the configuration to the BWB one, the forces in the fuselage and in the wings are parallel and they get a better distribution along the aircraft. The load distribution of these two cases is shown in figure 1.4(c). Although this concept is more fuel efficient, it is not applicable to commercial market mainly because of the fuselage’s cross-section. The conventional circular cross-section resists the internal pressure, but the oval cross section one does not. In this way, nowadays, the BWB is only used in the military domain [15]. In figure 1.4(d) there is an example of this unconventional concept.

![Figure 1.4](image)

(a) Piaggio P.180: example of a three-surface aircraft [16]  
(b) Prandtl-plane configuration [14]  
(c) Comparison of the aerodynamic and inertial loads in the conventional (left) and the BWB (right) configurations [15]  
(d) X-48B Blended Wing Body [17]

Figure 1.4: Other Unconventional Aircraft Configurations

In this thesis, the unconventional aircraft configuration studied is a concept with a high $AR$ wing. This design feature may be found, for example, in the canard configuration or in more disruptive solutions such as the previously mentioned Prandtl-Plane. Furthermore, due to the airports’ restrictions regarding
the aircraft's size and the higher probability of having dynamic aeroelastic phenomena such as flutter [18], it can be considered unconventional at some level. Despite the predicted lower structural performance, the introduction of a high $AR$ wing on an aircraft will raise the value of the configuration's lift over drag ratio ($\frac{L}{D}$), decreasing, consequently, the block of fuel consumed by the aircraft in each flight. Therefore, in the use phase of the aircraft's life cycle, the costs and the environmental impacts will be much lower.

1.3 Process-Based Models - PBM

Although conventional and unconventional aircrafts have particular pros and cons that are easily inferred, others need to be explored. A useful tool to perform that analysis is the PBM. A PBM starts by the process model, in which the process requirements and the boundaries are established after knowing the product's description. Afterwards, knowing the operation conditions imposed for the processing requirements, in the operations model, the resources consumption is established in order to have the global inventory analysis of the model. With that inventory, both financial and environmental models may be performed by having the costs and the environmental factors, respectively.

1.4 Objectives

The main goal of this thesis was to perform discrete changes on the initial wing concept [19] provided by the Brazilian company EMBRAER for project NOVEMOR and to get insights from different disciplines (aerodynamics, structures, costs and environmental impacts).

The first step was to create 11 different wing configurations by performing simple changes on the original wing model. This initial model had:

- An aspect ratio of 7.8;
- No ribs (internal reinforcing structures).

The 12 different case studies came out from 3 distinct manufacturing processes, 2 variations of external wing geometries and 2 internal wing configurations. Although the airfoils used for both wings are the same, the chord is smaller and the span is bigger for the second wing, since the wing area was the same for both external configurations. In figure 1.5 are represented the paths of the 12 case studies tested in this thesis.

According to figure 1.5 each step is correlated with change in terms of dimension (external or internal) or manufacturing process:

- **blue**: External geometry alterations:
  - wing with the external dimensions already obtained in a previous optimization process;
  - wing with the same airfoil as the previous but with a higher $AR$;
Figure 1.5: The 12 case studies analysed in this thesis

- red: Internal geometry alterations:
  - wing only with skin and spars;
  - wing with skin, spars and ribs;

- green: Different manufacturing processes:
  - wing made through the metal’s machining process;
  - wing made through the composite’s ATL (Automated Tape Laying) process;
  - wing made through the composite’s AFP (Automated Fibre Placing) process;

The methodology followed was to perform 3 distinct analyses on the 12 different wings (original wing and the other 11 concepts). The analyses performed on the wings were:

- **Aerodynamic:**
  - only the external wing configuration produced different results;
  - therefore, there were only 2 distinct results, one for the original external configuration wings and other for the high AR wings;
  - the goal of this analysis was to get the values of the $\frac{L}{D}$ ratio and the pitching moment ($C_M$);

- **Structural:**
  - different composite production methods give the same structural results;
  - only external and internal wing configurations and different materials produced distinct results;
  - therefore, there were 8 distinct wings analysed;
  - the goal of this analysis was to get the values of the maximum tip displacement and the maximum stress found for each different structure;
Economic and Environmental Analyses:

a) **LCC**: (out of the costs) was performed independently into its 3 life cycle phases:
   - Production;
   - Use;
   - **EOL**;

b) **LCA**: (out of the environmental impact) was performed independently into its 3 life cycle phases:
   - Production;
   - Use;
   - **EOL**.

- the goal of these analyses was to have a comparison in terms of total costs and environmental impact, for each wing configuration, in all their life cycle.

After the analyses were performed and the results obtained and interpreted, they were balanced in an **Analytical Hierarchy Process (AHP)** in order to get the best wing out of the 12 studied. The **AHP** is a technique used to organize, analyse and evaluate different concepts in various disciplines at the same time.

### 1.4.1 Research Question

In order to attain the aim of this thesis, the question to be formulated was:

"What are the decisive variations on an initial optimized wing concept that can produce an even better structural and aerodynamic configuration without increasing significantly the costs and the environmental impacts?"

Besides this main research question there are a few sub-questions to help finding the answer to the essential one such as:

- If we increase a wing's **AR** without modifying the main wing area, what will change?

- In what does the introduction of ribs on the original model will improve in the concept's structural behaviour and what impact does that upgrade have on the financial model (**LCC**) and on the environmental model (**LCA**)?

- What are the differences between metal's and composite's manufacturing processes?

- Considering the composite's manufacturing processes, in which stages do the **ATL** and the **AFP** models diverge?

- What are the pros and the cons of a composite wing when compared to the same geometry built in aluminium in terms of costs and environmental impact during its whole life cycle?
1.5 Thesis Outline

1.5.1 Report Structure

The report starts in chapter 2 with a literature review on PBCM. These are a variation of the PBM but are much more used nowadays to determine the costs of a given part. Afterwards, life cycle analyses in terms of costs (LCC) and environmental impact (LCA) are described. Also in this chapter, the different production processes for composite and aluminium are presented. In chapter 3 the thesis methodology is described in terms of the analyses performed on the 12 distinct models. In chapter 4, besides the presentation of the wings’ responses in the structural and aerodynamic domains, these configurations are evaluated in terms of economical and environmental impacts in their complete life cycle. It is also in this chapter that a parametric study is made in order to improve even more the data obtained. Conclusions on the overall research and achievements are written in chapter 5, followed by the recommendations for a future work.
Chapter 2

Background

2.1 Process-Based Cost Models - PBCM

The objective of the PBCM is to establish the path to follow between the product description and its final cost in order to optimize the operations in all its phases. There are several variables that are needed to be taken into account in the product’s description such as the component’s geometry, the material properties, the economic characteristics and also the operating conditions. The importance of establishing a PBCM is to have the necessary information to make the key decisions before the operations start to take place, regarding all the technological alternatives. In figure 2.1 are shown the stages of a PBCM [20].

![Figure 2.1: Stages of a technical cost model [20]](image)

The PBCM’s analysis is performed backwards, starting at the product’s cost and retreating steps until reaching the product’s description. There are three crucial steps to implement the PBCM, as it is possible to understand by figure 2.1:

- Process Model
- Operations Model
- Financial Model

Cost models are very useful tools to make the key decisions such as comparing the various options in terms of material, designs and processes. PBCM also help to characterize the strategic strengths and evaluating performance improvements, as well as choosing the significant developments. They are
also a simpler way to determine the cost drivers. The cost drivers of a certain process may belong to its fixed or variable costs. Fixed costs are the ones that do not depend on the amount of components produced, for example: equipment (machines), dedicated tools, building and overhead. On the other hand, the variable costs are those that are given in function of the production, such as material, labour, energy spent in the machines and other devices in the building and non-dedicated tools [21]. There are some trade-offs, which can be seen in figure 2.2, that follow the product’s development and production and conduce to its cost.

<table>
<thead>
<tr>
<th>Fundamental Cost Tradeoffs In Production</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>Material</td>
</tr>
<tr>
<td>- Time &amp; complexity</td>
<td>- Raw material cost</td>
</tr>
</tbody>
</table>
| - Sharing among related systems | - Ability to reuse | - Producibility, loss, &
| - Novelty vs. incremental refinement | process materials | defects, rework |
| - ... | - Properties & performance | - Tooling & equipment requirements |

Figure 2.2: Key trade-offs along the product’s development and production [20]

**PBCM** are a big advantage for every manufacturing process and there are some critical steps to follow. The first step is to define questions so that the model is able to give us the answers. It is crucial to understand the processing boundaries so that the answer to the question ‘Cost of what?’ is determined. Another important aspect is that the producer must be able to see the product in many different perspectives. The coupling of all the perspectives determines the pertinent costs of the model in such a way that the question ‘Cost to whom?’ is replied. In a further stage, there should be an analysis of the hypothetical changes in such a way that it becomes clear which of them correspond to advantages in the process. With this analysis it is easier to understand how the costs vary when a certain technical change is applied. Considering different options for the model it is viable to compare the costs of each one and choose the most profitable. Although these questions are important to define the model, there is still a dependence between the product’s cost and the context of its surroundings. In this way, it is necessary to establish the context in which it will occur, in an early stage of the process [21].

The second step of a **PBCM**’s creation is to identify the relevant costs. Those are the ones that are crucial for decisions and necessary for credibility. Costs such as labour, material, energy, equipment, overhead, tooling and building are considered relevant. In addition, there are other costs that are important such as the compromise concerning time and certain resources (in raw materials or special tools) [21].

The next stage is the definition of the process operations’ diagram and the material flows. For each operation of the process, labour, energy, tools and equipment are defined. The dare of the cost modelling is to determine the amount of equipment necessary to buy and the components’ production cost. The cost per unit and the number of parts to produce need to be known for each resource in the diagram.
Therefore, that kind of information is important to be obtained as soon as possible [21].

Finally, it is necessary to establish the relation between the costs and the current market. The whole process includes four stages [21]:

- Begin at the actual endpoint and start by the costs (backward analysis);
- Then it is required to estimate a value for the production costs. An initial approximation can be done simply by making the product between the quantity needed and the unit cost;
- After that estimation, the parameters must be analysed and evaluated as acceptable or unacceptable endpoints. Further on, the model should be able to deduce them from a simpler set of information;
- To end the cycle, the previous stage must be satisfied, otherwise the loop must start again at the first step with a new set of endpoints.

Some parameters such as the product’s mass and dimensions are requirements that can never be forgotten in the end of this backward analysis. Once the model is established, there are crucial verifications to make, such as the production capacity and the production volume [21]. The production capacity is related to the quantity of components produced in good conditions and the production volume is the quantity of components in good conditions effectively produced.

Time is always a big significant constraint to the model, not only because more resources are needed in order to raise the daily production, but also because it defines the capital requirements. Even in the equipments, time is a determinant factor [21]. The equipments’ requirements are established by the relation between the time needed and the time available. Time needed is the time spent on loading the machines and tools, making the product and unloading those equipments. On the other hand, time available is the one that involves shifts, breaks, downtime and maintenance [21]. Regarding the ratio of the minimum equipment requirement, it is given by the quotient between the time required for the annual production and the uptime. Total processing time is given by the sum of processing, load time, unload time, and time spent in the production of useless or unsold unities. Also, downtime is very critical to the line utilization due to scheduled and unscheduled breaks [21].

In a 24 hour day, the line utilization has downtime and uptime. Uptime is related to the total manufacturing time, not only for the analysed parts, but also to the other ones. Line utilization can also be divided in available and unavailable time [20]. In figure 2.3 are shown the parts that build a line utilization during a day.

![Line Utilization for a 24 hour day](image)

Figure 2.3: Composition of a line utilization in a 24 hour day [20]
Available time includes uptime and idle. In order to increase the line's efficiency, it is important to reduce the idle time, so that the uptime can correspond to almost all of the available time.

Regarding the capital costs, it is possible to distribute them over time using a simple amortization in which those costs are spread over the goods sold and not over the goods produced. The capital can be either dedicated in case of only having the possibility of being used to make a single good or non-dedicated if it can be used to produce other goods [21].

All the model is structured as a successive decomposition of the cost's problem, in which it is needed to refine the estimated values in order to reduce the number of independent cost elements. At the same time, that refinement helps in the construction of the diagram. The diagram is started backwards on the operation cost, then there is a refinement of the intermediate characteristics and finally is established the process description [21].

### 2.1.1 Process Model

A certain product has a determined cost in function of the market at which it will be allocated. However, it has its manufacturing process as a base of its cost. Therefore, there is an interrelation between the design of the product and the process used. This happens because the cost of operating a given process depends on the product’s design and also because the concept's cost is directly related to that same process. Regarding the process model, in order to establish a manufacturing process, there is a set of technologies that are needed to be taken into account to reach the production desired. This set can be made by simpler applications or it can be developed into more complex systems.

### 2.1.2 Operations Model

Between each technology input there are some operating conditions that fulfil the physical principles along the manufacturing process [20]. When the process requirements are applied to the process model, and the operating conditions are analysed, the operations model is ready to run. The modelling of operations is crucial to optimize the time spent in each step and, consequently, to reduce the energy used in the process. It is crucial to make correct decisions in order to get the best balance between the maintenance time and the operating time.

### 2.1.3 Financial Model

Resources such as tools, equipment and labour must be well determined in order to reach the financial model. After the determination of the resources required and establishing the cost of each of them, the final task is to transform the resources’ requirements into their price factor. Some of those factors are directly related to the production, such as labour and energy regarding the time of production and the materials, regarding the quantities produced, also known as variable costs. Other factors may not depend directly on the production (fixed costs) like building costs and tool expenses [20]. When the final stage of the PBM is the financial model, the whole methodology is a Process Based Cost Model (PBCM).
2.2 Life Cycle Analyses

Nowadays it is very important to determine the product’s impacts not only in the economical field, but also its environmental consequences during its complete life cycle. Therefore, the resources of a part’s production, use and EOL may be used to determine its LCC and LCA.

2.2.1 Life Cycle Cost - LCC

In order to determine the costs of the global product’s life cycle, the method used is the LCC. Variables such as the concept’s design or material have direct influence in all the product’s life cycle phases. The acquisition costs are most of the times used as unique and principal conditions for decision making on equipments’ investment [22].

In the LCC method, the production costs, the costs during the product’s useful life and the costs for its final disposal are determined and a long time decision can be justified [22]. This evaluation is suitable to compare between different products for the same application in terms of their total expenses, contributing with the possibility of easily identifying the main costs’ source in each life cycle phase [22]. Therefore, the LCC method has a large spectrum of engineering applications. However, this method requires a lot of data and a consistent research needs to be made before being used [22]. Figure 2.4 shows the logical steps to perform the LCC methodology.

![LCC steps](image)

Figure 2.4: LCC steps [23]
2.2.2 Life Cycle Assessment - LCA

LCA is a methodology to evaluate and comprehend the environmental issues of a concept's manufacture and activity. All this analysis performed by the LCA is made along the product's life cycle [24]. Most important of all, the LCA is a tool that enables a certain company to analyse, in a systematic way, the environmental impacts of their concepts, along their whole life cycle. This process is performed including several phases such as the raw material's extraction, the product's manufacture, use and EOL. In this way, LCA processes are considered as a 'cradle to grave' description of the environmental issues of a product’s generation [25].

Two significant resources that the LCA takes into account in its process description are the energy and the materials involved in the production. The material consumption can be subdivided in material used and material wasted. The LCA evaluates the exchanges of material between the environment and the company. The product's life cycle starts in the extraction of the raw materials that, further on, will be processed, manufactured, transported and finally distributed. Besides this, the LCA takes also into account the final use of the concept, its re-use, maintenance, recycling and final placement [24].

Although LCA only contemplates the environmental impacts, there are other aspects that derive from a concept's manufacture, such as economical, social, political and technical issues. In this dimension, the LCA works as a useful tool to check the impacts of a certain production, not only in the environmental domain but also in various collateral ones [24].

Companies should have set goals to reduce the environmental impact of their manufacturing processes and, after that, create alternatives to improve them. When companies have periodic analyses of the consequences of their products' life cycle win much more credibility and confidence from their clients. In order to call the producers' attention for pollution issues, environmental management standards were created. Examples of those are: ISO 14001 (International Standardization Organization), European Community eco-management and audit scheme EMAS [24]. ISO embraced an environmental management standard in the 90’s decade. This standard belonged to its group of 14000 standard series and the one that contains LCA's methodology is the 14040 series. Figure 2.5 shows the framework based on ISO 14001 standard [25].

![Figure 2.5: LCA framework based on ISO 14040](image)

Besides this, other methodologies were followed by several international organizations. ISO standard supports a four-stage interactive framework that provides LCA analysis [25]. These four steps must be followed in order to get a full LCA analysis [24]:

1. Goal and Scope Definition
2. Inventory Analysis
3. Life Cycle Impact Assessment
4. Interpretation
- Project the LCA process always with the main goal in mind and the scope well defined;
- Develop an inventory analysis to determine the process’ material and energy flows;
- Establish the Life Cycle Impact Assessment (LCIA) in order to evaluate the environmental impacts of the whole process;
- Finish the process with an improvement assessment and result’s interpretation to help to take certain decisions that will reduce the environmental impact and search for less pollutant alternatives.

In the first stage of the LCA it is crucial to define the system’s boundaries as well as the quality criteria to apply in the inventory data. Therefore, the establishment of the goal and scope is the starting point of all the analysis. In a second stage it is necessary to perform the life cycle inventory analysis. In this step, flows of energy and material between the company and the environment are taken into account, for all the product’s life cycle phases. Further on, in the LCIA there is a characterization of all the material and energy flows previously analysed. This separation is made in several categories in which a characterization factor is required to determine the contribution of each material or energy consumption. Those different environmental categories are: climate change, ecotoxicity, ozone reduction, formation of photochemical ozone, human toxicity, land use, resource consumption, acidification and eutrophication. The final stage of the LCA according to ISO standard is the life cycle interpretation, in which the results from LCIA and life cycle inventory analysis are verified, checked and interpreted [25].

With the presence of environmental management standards, companies are more alert to the need of environmental protection and develop the skill of reporting their contribution for the pollution due to their manufacturing processes. A LCA study sketches the steps involved in the production of a given concept, conducing to a final detailed report of the data concerning the environmental issues [24].

### 2.3 Production Processes

In the following sections it is going to be discussed both composite’s and metal’s production methods. Aluminium will be considered as the representative material for the metal’s group due to its presence in the actual aeronautical domain [26]. Aluminium is a very workable and weightless metal. The combination of these two properties fulfils the needs of the aeronautic market in terms of metal manufacturing. The incessant and continuous development of the aeronautical industry ensures the improvement of the technology used to work with the materials applied in the structural parts’ manufacture. Therefore, composites belong to a very significant percentage of the materials used in aerospace components, not only today but also in future applications [27]. Due to their superior physical properties when compared to other materials, composites are wining, day after day, more space in the structural domain of the aircraft industry. Some advantages of the composites are their very high ratios of strength and stiffness-to-density [27]. New production methods in the composite’s domain increase the knowledge about their advantages over metals in the aeronautical industry. So important for an aircraft as a light weight material is also a material that can have a good fatigue and corrosion resistance, producing much more
durable parts than the ones in aluminium [27]. Modern commercial aircrafts use a lot of matrix polymer composites, such as in the Airbus A310’s fin and in the Boeing 777’s and Airbus A340’s horizontal stabilizers. However, aluminium alloys still remain the election materials for the airframe [28].

2.3.1 Composites’ Production Processes

There is a wide set of production techniques and systems possible to use in the automatic manufacturing of components for the aeronautic industry. In the 1970’s, carbon fibre reinforced epoxy became the primary material in the main wing, fuselage and tail [4]. Before the composite’s automated manufacturing, the most common method used was the hand-layup. Hand Lay-up is a traditional open moulding method in which the production volume per mould is very low. Nevertheless, it is feasible to have substantial production quantities when using multiple moulds. This process is very used in the production of boats, bathware, tanks, car’s components, architectural products and other products with a high variety spectrum of sizes.

In the Hand Lay-up process a gel coat is applied to the mould in a primary stage. For that, a spray gun is required in order to obtain a surface with high-quality. When the gel coat is sufficiently cured a roll stock fibre reinforcement is ready to be placed manually in the mould. To apply the laminating resin it is necessary to have brushes or rollers [29]. To consolidate the laminate it can either be used Fibre Reinforced Plastic (FRP) rollers, squeegees or paint rollers. This consolidation can be achieved by moistening the reinforcement and by removing the entrapped air bubbles [29]. The laminate’s thickness is obtained by adding subsequent plies of fibre reinforcement. Usually to obtain a sandwich type structure, low core density materials can be used to strengthen the laminate. Foam, end-grain balsa and honeycomb are some examples of those reinforcement materials. Accelerators and catalysts are used to initiate the resin’s curing without the help of heating transfer, in order to harden the material [29]. After that, the composite is left at standard atmospheric conditions to cure. Regarding the fibre content in the Hand Lay-up process, it can be enhanced from $30 - 50\%$ to $55 - 60\%$ by the use of low temperature vacuum bags for ‘pre-impregnated’ composite fibres prepreg [30]. Prepreg is a fibre tape that has a certain quantity of uncured resin impregnated and it is more expensive. However, much of the additional production cost is diffused because the fibres are already mixed with the resin [31]. In figure 2.6 it is shown a scheme of the Hand Lay-up process.

![Figure 2.6: Hand Lay-up process [32]](image)

The hand Lay-up process has the advantages of being a simple method that works with cheap tools and the capability of producing parts with a wide range of sizes. It is a process that does not require a
very high investment and if the operators are skilled, it is possible to produce a lot of components with good quality. However, it is a process that depends a lot on the operator's skill and features such as resin mixing, laminate resin contents and laminate's quality may be affected [31].

Due to the market's demand, the manual methods needed to be faster and to have a larger daily production. With this emerged the need of developing automated manufacturing processes [33]. From all the processes used in the composite part's production the ATL and the AFP, which belong to the automatic lamination machine's group, will be the ones analysed further on. These models are capable of producing advanced composites, which have even greater mechanical properties than the common composites [34]. Actual aircraft concepts have more than 50% of their total weight made of advanced composites. The composite's market needs to improve its rate of production and to adjust its economy in order to reach the demand of these programs [34]. The main property of the advanced composites that mostly contributed for their spread into other engineering environments is their cost effectiveness. However, to enter these areas, the advanced composites must be automated in order to achieve their industrialization [34]. Two of the most significant technologies developed nowadays in the advanced composite laminates are the ATL and the AFP. In the ATL process, a wide prepreg tape is placed on a surface at the same time that the ply backing is eliminated [34]. Variables like layup speed, tape tension and tape temperature can be controlled while the layup is occurring. The AFP process has great similarities with the ATL one, but uses a set of finite prepreg slices that are placed on the head and then deposited simultaneously [34].

The first known ATL model is patented by Chitwood and Howeth in 1971. In this early design is illustrated the method of laminating composite tape on a rotatable base-plate by the use of Computer Numeric Control (CNC) [34]. In figure 2.7 is shown the system characterized by Goldsworthy in 1974. This computerized system passed a 76 mm wide tape on the top of a curved surface. The head had a rotation degree and, at the same time, the ability to retain some material. The importances of ATL models' development are the decrease of the number of layup errors and the significant reduce in the material waste for low complexity parts [34].

![Figure 2.7: ATL delivering tape on a curved surface][1]

It was crucial to turn this technology into a generic process in order to allow the ATL to become a boundless concept. It was required a higher layup speed. In 1984 Stone developed a commercial
An ATL model capable of delivering over geometries that had a curvature smaller than 15 degrees. This became possible due to the use of an ultrasonic tracking system all over the mould’s curved surface [36]. This was the first model of a Contour Tape Laminating Machine (CTLM). Two years later, in 1986, Meier invented a system in which the ultrasonic tracking was replaced by force-controlled Z and A axes [37]. With this development, features such as the head normality over curved surfaces and the control of the direct layup force were empowered. This upgrade started the basis of the modern commercial single-phase ATL models [34].

Another important step for the ATL models was the tape heating. This additional stage was only introduced in the 90’s decade and it was crucial to beat several issues that occurred during the layup of some very complex laminates [34].

Nowadays, ATL models have a lot of variations. The earliest concepts are currently being developed with the focus on a particular part’s layup [34].

Either ATL or AFP processes can be seen as inverse machining or also known as additive manufacturing [34]. This happens because during the machining process the part is built up by overlapping plies of material. Typical values for the prepreg tape manipulated by the ATL’s head is a width of 75, 150 or 300 mm. These values are similar to the ones used in manual layup prepreg [34]. In figure 2.8 is shown a scheme of the ATL system most common in the market, in which the prepreg tape is placed on the model’s head [38].

![Figure 2.8: ATL layup head’s scheme [38]](image)

When it is necessary to manufacture big parts such as aircraft components, ATL systems can be attached to vertical columns or horizontal bases, as it is possible to see in figure 2.9.

Also, most of the aircraft’s structures can be designed by the use of splines and may have a few ply terminations, conducing to highly complex geometries. The CNC system that forms the ATL process follows a sketch of predefined tracks in an accurate and reproductive way, eliminating errors in the layup that were probable to take place in the manual layup [34]. In the beginning of the layup stage, ATL systems use silicone roller to fix a section of the tape to the working tool. This part of the tape has a given length that is previously chosen and attributed in the system’s control [34]. After the path is defined, the ATL system increases its speed until the predefined layup speed is reached. In terms of velocities and accelerations the most common ATL systems have a limit linear layup speed of 0.83 - 1 m/s and reach accelerations of 0.5 m/s² [34]. Typically, for a thermoset tape of 75 mm wide it is needed
a 445 N force, and for a 300 mm wide tape the compaction value rounds the 1000 N. These values generate a pressure of approximately 0.1 MPa [34]. In the thermoplastic domain the working pressures are much higher and can reach 3.6 MPa [34].

In an ATL system it is very important to supply tension to the mechanism in order to prevent some problems such as the damage of the support paper. In addition, the tension improves the plies’ alignment and empowers the system to produce curved geometries [34]. It is also possible to heat the material during the layup process and it can be done either on the layup’s release or in the system’s head. When the ply’s path is finishing, the system’s head decelerates just before the end and the tape is cut automatically [34]. This process can be done by the use of rotating or pinching blades. The process is usually stopped when the automatic fault detection finds a layup error [34].

ATL processes are very productive models for prepreg layup. Some advantages of these processes are their high layup rates, capability of producing very large components with very good mechanical properties (due to prepreg), capability to work with materials with a very high areal weight and simple offline programming of the machines [34]. Regarding ATL systems, there are also some disadvantages to point such as limited geometries of the parts produced, much higher material wastage than AFP processes and it is required a very high initial capital investment [34].

The use of ATL systems in aircraft’s components is very large because they are applicable in the manufacture of the tail, wing’s skin and wing box [34]. The aerospace ATL equipment is mainly produced by MAGCincinnati (USA), Forest Liné (France) and MTorres (Spain) [34].

As similar as in the ATL process, in 1974 Goldsworthy patented the system shown in figure 2.7. Although this system was designed as an ATL one, it also exposed the possibility of manufacturing curved surfaces by the use of automatic systems for tape layup [34]. In figure 2.10 it can be seen the system that matches to the first AFP concept. In this model, the head had the capability of cutting the tape into slices of 3.2 mm and then disperse them at different speeds.

In the early 90’s, AFP systems were known as a mixture between ATL systems and FW [39]. This combination would result in a concept that incorporated the capabilities of cut-restart and compaction give by ATL systems and the differential payout given by the Filament Winding (FW) [34].
AFP commercial suppliers used knowledge learnt during the ATL systems’ development to improve their models. For example, upgrades such as material guiding and roller design. Still, in the 90’s decade, the crucial obstacles to these models were the layup’s precision, the tension in the tows, the dependability and the productivity [34].

Until 2000, AFP processes had mainly been used in the space and military domains as it is possible to see in table 2.1.

Table 2.1: AFP applications in 2000, mostly military [40].

<table>
<thead>
<tr>
<th>Aircraft Program</th>
<th>Components made with AFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-18 E/F</td>
<td>Inlet Duct, Aircraft Center Side Skins, Stabilator Skins</td>
</tr>
<tr>
<td>C-17 Globemaster</td>
<td>Fan Cowl Doors, Landing Gear Pods</td>
</tr>
<tr>
<td>Bell Agusta 609</td>
<td>Fuselage Panels</td>
</tr>
<tr>
<td>Premier I</td>
<td>Fuselage Sections</td>
</tr>
<tr>
<td>Hawker Horizon</td>
<td>Fuselage Sections</td>
</tr>
<tr>
<td>Sea Launch</td>
<td>Payload Fairing</td>
</tr>
<tr>
<td>F22 Raptor</td>
<td>Stabilator Pivot Shaft</td>
</tr>
<tr>
<td>V-22 Osprey</td>
<td>Aircraft Fuselage, Side Skins, Drag Angle, Sponsons, Grips</td>
</tr>
</tbody>
</table>

AFP’s reliability was negatively affected by errors caused by the welding of the tape’s ends. To face this issue, Torres Martinez developed an automated system to splice the tows together in order to decrease the downtime caused by the material replenish [34].

The first difference between AFP and ATL systems is in the width of the tape used. In AFP models the tape is much straighter, assuming typical values of 3.2, 6.4 and 12.7 mm [34]. Despite this, AFP systems can discharge more than one tow per sequence [34].

Nowadays AFP models are capable of returning 32 tows in parallel. This process works at a linear speed of 1 m/s and accelerations may assume values of 2 m/s² [41]. Each of the manufactured tows is worked separately, thus they can have their own deliver speed. Other processes like clamping and cutting the tows provide the independence between them [34].

The tows independence in terms of manufacture speed allows AFP models to layup the tape over geometries of a high complexity level, as it is possible to see in figure 2.11. This curve layup feature enables complex surfaces to be made of composite tape layup with automatic processes, such as aircraft’s fuselage and, more important to this research, wing’s skins. The wing’s skin is a very sophisticated surface not only to project but also to manufacture. Thus, AFP systems entered the aircraft’s market also in order to solve this production issue [34]. Due to the complexity of the components manufactured,
AFP models usually have lower values of productivity when compared to ATL models [34]. The layup operation is similar to both automated models. AFP systems often use flexible rollers in order to aid the material's compression [34]. The principal manufacturers of AFP systems around the globe are: Accudyne (USA), Electroimpact (USA), MTorres (Spain), Ingersoll (USA), Forster Miller/ATK (USA), Coriolis (France), MAGCincinnati (USA) and Automated Dynamics (USA) [34].

The market's demand established the need of raising the lay-up's productivity. Therefore, automation was seen as the most efficient path to follow in order to achieve it. The biggest obstacles to the manual processes are the high labour costs and the low productivity [42]. In order to transform these processes into automated ones, it is required a strong initial investment in machines, in labour and in scrap material. On the other hand, the layup speed is much higher, increasing the company's production in a very significant way [42].

Either for ATL or AFP systems, the main priority is to raise their productivity. In this way, all the improvements studied at the last few years had as a basis the production growth. Most of them were achieved by the software's development, layup improvement material selection and machine's final stage design [34]. In figure 2.12 it is possible to see the growth in the productivity of both ATL and AFP models in face of the part's size and the maximum layup speed, respectively. As figure 2.12 shows, AFP models are more productive than the ATL ones for all the sizes, but this aspect is even more crucial for the smaller components [34].

When the manufacturer needs to produce a flat and large part, ATL is the most suitable system to use, since in this process the tape is much wider and easier to place big quantities of material in each course [43]. The material used for ATL systems is cheaper than the one used in AFP models (tows). Therefore, for a large amount of components produced it has a significant weight when it is necessary to choose between these two processes [43].

On the other hand, AFP models are a better option either for curved or more complex geometries because they can lay-up narrow tows [34]. These have better manoeuvrability, conducing the a lower material wastage [44]. In figure 2.13 it is possible to understand why AFP has much lower waste of material when compared to ATL models. The tape's width is a variable that is directly related to it.

The most common tow steering defects can be seen in figure 2.14 and can be distinguished into tow misalignment, tow buckling and tow pull up. This issues have different impacts in the mechanical behaviour of the laminates but it is not a technical domain sufficiently explored [34].
Automated systems such as ATL and AFP are growing year after year their credibility and consecutive bet among the industrial companies, not only due to their economic but also reliability improvements [34]. Since the 70’s, ATL models have replaced manual tape laying in most of industrial companies. ATL systems are specially productive for large plane components. In the domain of high areal weight materials, ATL systems are the indicated ones. For more complex components with curved surfaces, AFP models are better. Capabilities such as single cutting, clamping and restarting for each tow make AFP models those that satisfy better the requirements of the aerospace components [34].

For a better understanding of each one of the three layup processes studied in this section, table 2.2 presents their advantages as well as their disadvantages.

### 2.3.2 Metal’s Production Process

Since machining (milling) is one of the most used manufacturing processes of metals in the aeronautic industry, it will be the one explored in this section. Aluminium is a crucial material in the aerospace in-
Table 2.2: Comparison between Hand-layup, ATL and AFP [44], [43] and [34].

<table>
<thead>
<tr>
<th></th>
<th>Hand Lay-up</th>
<th>ATL</th>
<th>AFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part’s Size &amp; Design</td>
<td>All sizes; Flat &amp; Curve</td>
<td>Flat &amp; Large</td>
<td>Medium/Large; Complex &amp; Curve</td>
</tr>
<tr>
<td>Number of tows/tapes</td>
<td>1</td>
<td>1</td>
<td>12, 24 or even 32</td>
</tr>
<tr>
<td>Speed [m/s] (max.)</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Acceleration [m/s²]</td>
<td>-</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Course Length [mm] (min.)</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Tape’s/Tow’s Width [mm]</td>
<td>-</td>
<td>either 75, 150 or 300</td>
<td>from 3.2 to 12.7</td>
</tr>
<tr>
<td>Scrap material [%]</td>
<td>25-30</td>
<td>2-25</td>
<td>2-5</td>
</tr>
<tr>
<td>Labour</td>
<td>High costs</td>
<td>Low costs</td>
<td>Low costs</td>
</tr>
<tr>
<td>Initial Investment</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Productivity</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

The industry because it is very easy to manipulate. Before the machining process is initiated, the raw material needs to be placed in a JIG [45]. This holding tool is crucial to the process not only because it supports the raw material, but also because it keeps the part in its right position to be worked [45]. The JIG tool increases the production because stages such as part’s set-up and check are expendable. Therefore, costs coming from quality checking no longer exist [46]. In consequence, the production’s speed will raise as well as the parts’ quality, because they are stuck in the JIG [45]. Machining enables the production of a certain complex part out of a solid block of metal. This production method is also used to improve the part’s tolerances as well as its surface’s finish. It is capable of producing configurations that, most of the times, are not possible to obtain by other techniques. In the machining process, when the components are being manufactured, the excess of material is removed in the form of chips [47].

In the aeronautic industry besides the need of quality on the surface’s finish, the manufacturing cost and duration are crucial parameters. Directly related to the component’s final quality and production are the design and the machine’s properties such as rotation speed, capability of fixing the part and computational time of the numerical control [48]. In figure 2.15 are shown two different types of milling according to the axis orientation. Automated milling machines can have horizontal or vertical axis according to the direction of sculpting the part. The number of axis is related to the total number of different movements that the milling machine can perform (usually 3 or 5) [47].

![Figure 2.15: Left: Horizontal-axis Milling; Right: Vertical-axis Milling [47]](image_url)

The material removal is done by the use of sharp teeth in order to obtain the projected geometry. The milling machine must have high control of its mechanism in order to manufacture the part with the desired quality finish. In each clamping stage, operations such as roughing and finishing take place. The number of clamping stages depend on the component’s design [48] and in each of them the tool
to remove the material may be different, contributing to the creation of different series of machining parameters [48]. Examples of these parameters are the cutting and spindle speeds, the tool’s diameter, the feed per tooth and the material removal rate [48].

Manufacturing processes in metals have some differences when compared to the composite ones. There are some additional and different steps that need to be taken into account as well as specific formulas. The machining cycle time can be determined in several different ways, depending on the data that is provided [20]. The first method is by summing the cycle time in each clamping stage and the machining cycle time. Another way is to calculate the machining cycle time \( CT \) is by having the removal rate \( MRR_{ij} \) and the area/volume removed \( AVR \) in each clamping stage \( i \) and for each operator \( j \). In equation 2.1 is expressed that relation.

\[
CT = \sum_{i=1}^{m} \sum_{j=1}^{n} AVR_{ij} \cdot MRR_{ij}, \tag{2.1}
\]

where \( CT \) is the cycle time, \( AVR \) is the area or volume removed and \( MRR \) is the material removal rate.

When the only data that is provided is the one from the tools, the \( CT \) is determined also by the use of equation 2.1. However, the removal rate \( MRR_{ij} \) is determined by the Sandvik formulas given in the system 2.2.

\[
\begin{aligned}
  n &= \frac{v_c \times 1000}{\pi D_{cap}} \\
  v_f &= f_z \cdot n \cdot z_c \\
  MRR &= \frac{a_p \cdot a_e \cdot v_f}{1000},
\end{aligned} \tag{2.2}
\]

where \( n \) is the spindle speed, \( v_c \) is the cutting speed, \( D_{cap} \) is the cutting diameter at actual depth of cut, \( v_f \) is the feed speed, \( f_z \) is the feed per tooth, \( z_c \) is the number of effective teeth, \( a_p \) is the cut’s depth and \( a_e \) is the working engagement.

In respect to the mould’s total time, it is given by the product between the number of stages and the mould’s set-up time, expressed in equation 2.3.

\[
JIG_{totaltime} = n_{stages} \cdot JIG_{setuptime}, \tag{2.3}
\]

where \( JIG_{setuptime} \) is the holding tools’ set-up, \( n_{stages} \) is the number of stages in moulding and \( JIG_{totaltime} \) is the holding tools’ total time of operation.

Other cost that can affect the final calculations is the paint cost, which depends on the cost per litre, on the paint’s thickness, on the surface’s area to paint and on the number of units produced and available for sale [20].
Chapter 3

Methodology

All the concepts generated will be analysed in this chapter in terms of aerodynamics, structural behaviour, life-cycle costs and environmental impact of their production, use and EOL. Some of them will be better from the structural point of view, while others from the aerodynamic one. Also, the environmental impact and the costs in each phase will be determined by the use of the Process Based Model tool.

The methodology followed in this thesis is presented in figure 3.1.

---

In order to achieve the best wing model out from a discrete analysis, the first step was to generate 11 different models from the original one provided by EMBRAER in project NOVEMOR. Afterwards, those 12 wing configurations (the original wing and the generated concepts) were submitted to 4 distinct analyses: Aerodynamic, Structural, Economic, and Environmental, during their complete life cycle. Once the results of the analyses were obtained, a parametric study was performed to refine them and to take extra conclusions from the tests performed. On a final stage of the thesis, the pros and cons of each wing were analysed and balanced in order to conclude which of them is the best wing model.
3.1 Models

3.1.1 External and Internal Configurations

In this chapter, the different configurations introduced in section 1.4 will be analysed in light of four different fields: aerodynamics, structural, LCC and LCA. The original model was developed by the Brazilian aircraft manufacturer EMBRAER in the scope of the EU FP7 project NOVEMOR. Beyond the already optimized airfoil along the wing span, the structural model was composed by: wing skin and front and rear spars, forming a wing-box. In figure 3.2 it is possible to check the initial data configuration modelled in the Finite Element (FE) software Siemens NX.

![Figure 3.2: Original configuration provided by EMBRAER](image)

To provide a better understanding of the wing dimensions, figure 3.3 shows the nomenclature used for those variables.

![Figure 3.3: Wing dimensions](image)

The simplified wing model has an aspect-ratio of $7.8$ ($AR = 7.8$). In order to attain a longer range in each flight for the same block of fuel, it was tested a new external wing configuration with:

- The same wing area $S$ as the original configuration;
- The same sweep angles at the leading edge $\Lambda_{LE}$ as the original one;
- The same airfoils;
- A different aspect ratio, assuming a value of $16$ ($AR = 16.0$) for the higher $AR$ concept.
In figure 3.4 is shown an example of a wing’s aspect ratio variation, maintaining the same wing area.

![Figure 3.4: Different Aspect Ratio Wings with the same Wing Area](image)

The increase of the $AR$ for a value more than double of the initial one, generates a longer and thinner wing, in this case, for the same wing area. For a higher aspect ratio wing configuration, the range will be bigger due to its lower aerodynamic induced drag and higher $\frac{L}{D}$. In order to determine the wing area $S$, the geometry was divided into two different trapezes for which the area was determined and then summed up. The shape can be seen in figure 3.3.

The system of equations 3.1 describes the relations between the wings’ dimensions and table 3.1 presents their values.

\[
\begin{align*}
    b &= 2 \cdot (L_1 + L_2) \\
    S &= b \cdot \bar{c} \\
    AR &= \frac{b^2}{S} \\
    \lambda &= \frac{c_t}{c_r}
\end{align*}
\]

(3.1)

where $b$ is the wing span, $L_1$ is the root to break length, $L_2$ is the break to tip length, $S$ is the wing area, $AR$ is the aspect ratio, $\bar{c}$ is the mean chord, $c_t$ is the chord on the wing’s tip, $c_r$ is the chord on the wing’s root and $\lambda$ is the tapper ratio.

The original configuration had no ribs. Therefore, other concepts were developed from this one, with the introduction of 10 ribs as it is possible to view in figure 3.5.

The position of these structural components regarding the $y$ axis is given in table 3.2.

In this way, four different configurations were established in order to be analysed further on:

- Wing 1 without ribs: original simplified wing-box layout;
- Wing 1 with ribs: original wing with the introduction of 10 ribs with locations described as in table 3.2 and with $AR = 7.8$ (original value);
- Wing 2 without ribs: concept similar to the original one, but with $AR = 16.0$ (higher value);
Table 3.1: Wing Dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Original Wing</th>
<th>High $AR$ Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ [m]</td>
<td>6.181</td>
<td>8.819</td>
</tr>
<tr>
<td>$L_2$ [m]</td>
<td>9.546</td>
<td>13.628</td>
</tr>
<tr>
<td>$b$ [m]</td>
<td>31.454</td>
<td>44.894</td>
</tr>
<tr>
<td>$c_r$ [m]</td>
<td>7.527</td>
<td>5.305</td>
</tr>
<tr>
<td>$c_{break}$ [m]</td>
<td>3.995</td>
<td>2.796</td>
</tr>
<tr>
<td>$c_s$ [m]</td>
<td>1.727</td>
<td>1.205</td>
</tr>
<tr>
<td>$\tau$ [m]</td>
<td>4.010</td>
<td>2.806</td>
</tr>
<tr>
<td>$S$ [m$^2$]</td>
<td>126.124</td>
<td>125.968</td>
</tr>
<tr>
<td>$AR$</td>
<td>7.8</td>
<td>16.0</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>$\Lambda_{LE}$ [deg.]</td>
<td>22.3</td>
<td>22.3</td>
</tr>
</tbody>
</table>

Figure 3.5: Original configuration with the introduction of 10 ribs parallel to the $xz$ plane

Table 3.2: Ribs’ location in $y$ direction

<table>
<thead>
<tr>
<th>Ribs</th>
<th>1 (root)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (tip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y$ coordinate [m]</td>
<td>0</td>
<td>$L_1$</td>
<td>$L_1$</td>
<td>$3L_1$</td>
<td>$L_1 + \frac{L_2}{2}$</td>
<td>$L_1 + \frac{2L_2}{3}$</td>
<td>$L_1 + \frac{3L_2}{5}$</td>
<td>$L_1 + \frac{4L_2}{7}$</td>
<td>$\frac{b}{2}$</td>
<td>$\frac{b}{2}$</td>
</tr>
</tbody>
</table>

- Wing 2 with ribs: wing with the 10 ribs and with $AR = 16.0$ (higher value).

3.1.2 Materials

For the 4 different concepts described in subsection 3.1.1, two types of material where applied, giving a total of 8 distinct models to analyse:

- aluminium $A6061$;
- composite with carbon fibres $IM7$ and epoxy resin.

Aluminium $A6061$ belongs to the family of the aerospace aluminium alloys [50]. This alloy is very resistant to corrosion and very easy to mould. Therefore, with this material, it is possible to obtain a good finishing. This aluminium alloy can be manufactured using a large range of techniques and it is usually applied in the aircraft’s structural components such as ribs, spars and wing’s skin [50]. Its mechanical properties are shown in table 3.3.

For the configurations in which the material selected was aluminium $A6061$ alloy, the thickness of all the components was assumed constant with a value of 8 mm.
Table 3.3: Aluminium $A6061$ properties

<table>
<thead>
<tr>
<th></th>
<th>Density ($\rho_{Al}$) [kg/m$^3$]</th>
<th>Young Modulus ($E_{Al}$) [GPa]</th>
<th>Poisson Coefficient ($\nu_{Al}$)</th>
<th>Rigidity Modulus ($G_{Al}$) [GPa]</th>
<th>Yield Stress ($\sigma_{yAl}$) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2700</td>
<td>68.9</td>
<td>0.33</td>
<td>26.0</td>
<td>276</td>
</tr>
</tbody>
</table>

For the composite, the idea was to create a laminate plate in which the total thickness (sum of the thickness of all the layers) is very similar to 8 mm in order to avoid introducing another variable in the comparison system between both materials. To create a material with plies in many different directions, the initial idea of stacking was to have plies with orientations in: $-45^\circ$, $0^\circ$, $45^\circ$ and $90^\circ$; in a symmetric configuration and with a layer thickness of $h_{layer} = 0.135$ mm. Thus, the initial stacking configuration was: $[-45/0/45/90]_S$. However, this stacking had only a total thickness of: $2 \cdot 4 \cdot h_{layer} = 1.08$ mm. Therefore, to get a total thickness very similar to the one established for the aluminium model, this stacking was used 7 times, resulting in a final thickness of $7 \cdot 1.08 = 7.56$ mm and a final stacking sequence that is given by expression 3.2.

$$[[−45/0/45/90]_S]_7$$ (3.2)

The composite’s properties are shown in table 3.4.

Table 3.4: Composite properties

<table>
<thead>
<tr>
<th></th>
<th>IM7 carbon fibres</th>
<th>Epoxy resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$) [kg/m$^3$]</td>
<td>1790</td>
<td>1200</td>
</tr>
<tr>
<td>Young Modulus ($E$) [GPa]</td>
<td>300</td>
<td>4.5</td>
</tr>
<tr>
<td>Poisson Coefficient ($\nu$)</td>
<td>0.35</td>
<td>0.40</td>
</tr>
<tr>
<td>Rigidity Modulus ($G$) [GPa]</td>
<td>111.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Yield Stress ($\sigma_y$) [MPa]</td>
<td>2760</td>
<td>-</td>
</tr>
<tr>
<td>Percentage in Volume ($V_%$) [%]</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

As for the aluminium model, for the composite configurations, the thickness used is the same for all the wing components: skin, spars and ribs. With the concepts and materials characterized, it is possible to start the analyses. The first one will be in aerodynamics.

### 3.2 Aerodynamic Methodology

Since the existence of ribs as intern structural components of the wing does not affect the aerodynamic analysis, the external geometry will be the only variable in this comparison. Therefore, for the aerodynamic behaviour, only two different models will be taken into account:

- Wing 1: concept with the original $AR$ given by $EMBRAER$ (7.8);
- Wing 2: concept with higher $AR$ (16.0).
Both configurations had the same airfoil distribution along the wing span, the same wing area $S$, the same sweep angles at the leading edge, but different $AR$. In figure 3.6 it is possible to see the root’s airfoil shape for both external configurations, since it is plotted in terms of the root chord.

![Figure 3.6: Root Airfoil](image)

For a better comparison between these two configurations, flight parameters such as altitude and speed must be the same. The Brazilian company chose an altitude of $h_{cr} = 38,000$ m and a Mach number of $M_{cr} = 0.78$ in their NOVEMOR project, for cruise level conditions. At this altitude, the air density is $\rho_{cr} = 0.00688 \text{ kg/m}^3$. Therefore, the analysis will be performed at a cruise speed of $V_{cr} = 245.04 \text{ m/s}$.

The methodology followed in this section is the one described by Corke in his textbook [51], in chapter 4 (Main Wing Design). For that, some assumptions had to be made, such as:

- Assume constant data for the maximum thickness over chord ratio (value: $(\frac{t}{c})_{max} = 0.167$; position: $(\frac{x}{c})(\frac{t}{c})_{max} = 0.4$) along the wing span and equal to the values took from the root airfoil;
- Assume a wing with carry-through structure (Low-Wing), giving a value of the interference factor for the main wing of $Q_w = 1$;
- Assume the square wing configuration ($S = b \cdot c$) in order to determine $c$;
- Assume the a mean sweep angle for the calculations given by: $\Lambda_{LE} = \Lambda_{root} + \Lambda_{break} \cdot 2$;
- Assume constant sweep angle along the wing and equal to the one at the leading edge ($\Lambda_{LE}$);
- Assume the convention for the location of the aerodynamic centre at $x_{ac} = \frac{c}{4}$;
- Assume the safety convention for the location of the centre of gravity ($x_{CG} = \frac{x_{ac}}{4}$);
- Assume an Oswald efficiency of $e = 0.8$, since for conventional fixed wing aircraft it may vary between $0.7 < e < 0.85$.

Once the dimensions for both wings are determined, it is necessary to calculate their aerodynamic coefficients: $C_D$ (drag coefficient), $C_L$ (lift coefficient) and $C_M$ (moment coefficient). Following Corke’s methodology [51], the first step is to determine the effective Mach Number $M_{eff}$ by expression 3.3. This value results from the wing’s $\Lambda_{LE}$.

$$M_{eff} = M_{cr} \cdot \cos(\Lambda_{LE}), \quad (3.3)$$

where $M_{cr}$ is the Mach Number at cruise level.
After obtaining \( M_{eff} \), in order to take into account the compressibility, the parameter \( \beta \) (compressibility factor) must be calculated by expression 3.4.

\[
\beta = \sqrt{1 - M_{eff}^2} \tag{3.4}
\]

Due to the assumption of considering constant \( \Lambda_{LE} \) along the wing, the expression to determine the form factor \( F \) is simplified into equation 3.5.

\[
F = \left[ 1 + \frac{0.6}{(\frac{l}{c})_{max}} \cdot \left( \frac{t}{c} \right)_{max} + 100 \cdot \left( \frac{t}{c} \right)_{max}^4 \right] \cdot \left[ 1.34 \cdot M_{eff}^{0.18} \cdot (\cos(\Lambda_{LE}))^{0.28} \right] \tag{3.5}
\]

To check if the flow is laminar or turbulent it is necessary to determine the Reynolds Number at cruise conditions \( (Re_{cr}) \). Considering the air viscosity for cruise altitude \( \nu = 1.5 \cdot 10^{-5} \, \text{m}^2/\text{s} \), \( Re_{cr} \) will be given by equation 3.6.

\[
Re_{cr} = \frac{V_{cr} \cdot c}{\nu} \iff \begin{cases} Re_{cr_{wing1}} = 65.5 \cdot 10^6 \\ Re_{cr_{wing2}} = 45.8 \cdot 10^6 \end{cases} \tag{3.6}
\]

Since \( \sqrt{Re_{cr}} > 1000 \) for both wing configurations, the wings are operating in a turbulent regime [51]. Therefore, the expression to determine the viscous drag coefficient, \( C_f \), is given in 3.7.

\[
C_f = \frac{0.455}{(\log(Re_{cr}))^{2.58} \cdot (1 + 0.144 \cdot M_{eff}^{8.5})} \tag{3.7}
\]

Regarding the wetted wing area over wing planform area ratio \( \left( \frac{S_{wet}}{S} \right) \), its determination is dependent on the airfoil’s maximum thickness \( \left( \frac{t}{c} \right)_{max} \). The wing’s root airfoil is considered thick for both concepts because: \( \left( \frac{t}{c} \right)_{max} > 0.05 \) [51]. Thus, \( \frac{S_{wet}}{S} \) can be calculated by equation 3.8.

\[
\frac{S_{wet}}{S} = 1.977 + 0.52 \cdot \left( \frac{t}{c} \right)_{max} \tag{3.8}
\]

Table 3.5 presents the results for the coefficients given by expressions 3.3, 3.4, 3.5, 3.7 and 3.8. It is possible to see that the only parameter that changes between the concepts is \( C_f \) because it is the only one that depends on the Reynolds Number, which is characteristic of each configuration. All the others depend on variables that are the same for both wings.

<table>
<thead>
<tr>
<th>Table 3.5: Wing Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
</tr>
<tr>
<td>( M_{eff} )</td>
</tr>
<tr>
<td>( \beta )</td>
</tr>
<tr>
<td>( F )</td>
</tr>
<tr>
<td>( C_f )</td>
</tr>
<tr>
<td>( \frac{S_{wet}}{S} )</td>
</tr>
</tbody>
</table>

With these values, it is possible to determine the wing base drag coefficient \( C_{D0} \) for both configurations. \( C_{D0} \) is a function of the skin friction coefficient \( C_f \), the form factor \( F \), the interference factor \( Q_w \).
and the wetted wing area over the wing planform area ratio \( \frac{S_{wet}}{S} \). To determine \( C_{D0} \), the expression 3.9 was the one used. In the beginning of this section it was assumed a Low-Wing arrangement, giving and interference factor of \( Q_w = 1 \).

\[
C_{D0} = C_f \cdot F \cdot Q \cdot \frac{S_{wet}}{S} \iff \begin{cases} \frac{C_{D0}_{wing1}}{S} = 0.00730 \\ \frac{C_{D0}_{wing2}}{S} = 0.00769 \end{cases}
\]

Expression 3.10 gives the wing's drag polar.

\[
C_D = C_{D0} + \frac{C_L^2}{\pi \cdot AR \cdot \epsilon}
\]

Substituting values in equation 3.10, the drag polars (i.e. the drag coefficient \( C_D \) as a function of the lift coefficient \( C_L \)) for the original concept and for the high \( AR \) one are, respectively, presented in equation 3.11.

\[
\begin{cases} 
C_{D_{wing1}} &= 0.00730 + 0.0507 \cdot C_L^2 \\
C_{D_{wing2}} &= 0.00769 + 0.0249 \cdot C_L^2 
\end{cases}
\]

In figure 3.7 it is possible to view these drag polars for both wing designs, from which it is possible to note that in the wing with lower \( AR \) (the original one) the drag coefficient increases more with the lift coefficient in comparison with the high \( AR \) configuration. Also, figure 3.7(b) shows that for very low lift coefficients the original wing produces less drag than the high \( AR \) wing. This happens because, maintaining the wing area, an increase of the aspect ratio will decrease the chord. A reduction in the chord length decreases the Reynolds Number which causes a higher aerodynamic viscous resistance. However, this phenomena dissipates with the increase of \( C_L \), where the decrease of the induced drag (on the high \( AR \) wing) is higher than the increase of the viscous resistance.

In order to determine the wing’s lift, it is crucial to determine previously the lift curve slope coefficient \( C_{L_\alpha} \) by the use of expression 3.12.

\[
C_{L_\alpha} = \frac{2 \cdot \pi \cdot AR}{2 + \sqrt{4 + (AR \cdot \beta)^2 \cdot \left(1 + \tan^2(\Lambda_{LE})\right)}} \iff \begin{cases} 
C_{L_{\alpha}_{wing1}} &= 5.94 \text{ rad}^{-1} \\
C_{L_{\alpha}_{wing2}} &= 7.02 \text{ rad}^{-1} 
\end{cases}
\]

In equation 3.13 is given the relation between the angle of attack \( \alpha \) and the lift coefficient that establishes the lift polar.

\[
C_L = C_{L_\alpha} \cdot \alpha + C_{L_{\alpha=0}}
\]

The lift coefficient for zero angle of attack was assumed to be the same for both wings and has a value of \( C_{L_{\alpha=0}} = 0.2131268 \). By replacing values in expression 3.13 it is obtained the lift polars for both wings, shown in equation 3.14 and represented in figure 3.8.
In order to determine the moment coefficient, $C_M$, for both configurations, some assumptions were made at the beginning of this section regarding the gravity centre and aerodynamic centre positions on each wing, demonstrated in the system of equations 3.15. With this configuration, the system is at a very stable stage.
Figure 3.8: Lift Polar for both external wing configurations

\[
\begin{aligned}
    x_{ac} &= \frac{x}{4} \\
x_{CG} &= \frac{x_{ac}}{4}
\end{aligned}
\] (3.15)

Once these positions are defined for each configuration, it is possible to determine the moment \( M \) in the wing by equation 3.16.

\[
M = -L \cdot (x_{ac} - x_{CG})
\] (3.16)

The aerodynamic results will give values such as lift, drag and moment coefficients. However, the most important value to analyse is the \( \frac{L}{D} \) ratio. In a cruise out to destination level, the fuel weight fraction between the beginning and the end of this phase will be directly related to the \( \frac{L}{D} \) ratio in the *Breguet* range equation shown in expression 3.17.

\[
R = \frac{V_{cr}}{C_{TSFC}} \cdot \frac{L}{D} \cdot \ln \left[ \frac{W_i}{W_f} \right]
\] (3.17)

By checking the *Breguet* range equation 3.17 is possible to understand that, for the same range \( R \), the same cruise speed \( V_{cr} \) and thrust-specific fuel consumption \( C_{TSFC} \), a higher \( \frac{L}{D} \) value induces a lower \( \frac{W_i}{W_f} \) value, so for the same initial fuel weight \( W_i \), the fuel weight at the end of the cruise phase \( W_f \) will be higher, so the block of fuel used will not be so higher as it would be for lower \( \frac{L}{D} \) values. The influence of the \( \frac{L}{D} \) ratio in the fuel consumption will also affect not only the concept’s *LCC* but also its *LCA*, as it will be analysed in the next sections. Once the aerodynamic methodology chosen is established, it is important do verify the structural implementation.
3.3 Structural Methodology

The Finite Element (FE) software used to perform the structural analysis was Siemens NX. In this FE software the first step was to build the geometry of the concepts to analyse further on. Therefore, 4 files .part were generated in order to create the 4 wing configurations established at the end of subsection 3.1.1. Once the 4 different geometries are designed, the next stage was to create a file .fem for each part in order to generate a mesh and apply a material to each geometry. Since each geometry was analysed with two different material compositions (aluminium and composite), there were 2 different meshes per configuration. To perform the simulations, it was necessary to generate a file .sim for each .fem file, in which the loads and constraints were applied to the part.

3.3.1 Meshing

The mesh refinement had different criteria for the 2 materials used. The configurations in which the geometry had extra components such as ribs, the meshing needed to be more complex. The regions’ division followed to generate the meshes is shown in figure 3.9.

![Mesh regions division for a geometry without ribs](image1)

![Mesh regions division for a geometry with ribs](image2)

Figure 3.9: Subdivision of the geometries to generate the mesh

For the configurations made in aluminium, the criteria adopted was the von Mises stress. This criteria is one of the most commonly used to refine the geometry’s mesh, when it is made in metal [52]. In figure 3.10 it is possible to analyse the convergence for 3 different meshes for each geometry made in aluminium A6061.

For each configuration, a mesh was performed. Then, 2 other meshes were obtained from the first one, by refinement. The main goal of this convergence analysis was to have an error always below 5%.

In table 3.6, the errors are shown and the goal of this convergence was achieved.

<table>
<thead>
<tr>
<th>Meshes</th>
<th>Wing 1, no Ribs e [%]</th>
<th>Wing 1, Ribs e [%]</th>
<th>Wing 2, no Ribs e [%]</th>
<th>Wing 2, Ribs e [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh 1</td>
<td>67.71</td>
<td>62.74</td>
<td>179.70</td>
<td>189.49</td>
</tr>
<tr>
<td>Mesh 2</td>
<td>68.98</td>
<td>64.70</td>
<td>179.53</td>
<td>190.40</td>
</tr>
<tr>
<td>Final</td>
<td>69.86</td>
<td>66.20</td>
<td>179.61</td>
<td>192.144</td>
</tr>
</tbody>
</table>

For the configurations made with the composite material described in the subsection 3.1.2, the criteria adopted for the mesh refinement was the deformation energy’s density, since it analyses the whole
Figure 3.10: Mesh refinement, by the von Mises stress, for the 4 aluminium configurations

composite structure and not each layer individually. The methodology was the same as the one used for the aluminium configurations and the convergence can be seen in figure 3.11.

Figure 3.11: Mesh refinement, by the deformation energy’s density, for the 4 composite configurations

Also, for these 4 composite models, an initial mesh was generated and then 2 meshes were designed from the first one, following a refinement with an error always below 5%. Table 3.7 shows that the errors keep their values under this limit of convergence.

Table 3.7: Mesh refinement for the composite configurations, by deformation energy’s density (kJ/m³)

<table>
<thead>
<tr>
<th>Meshes</th>
<th>Wing 1, no Ribs</th>
<th>e [%]</th>
<th>Wing 1, Ribs</th>
<th>e [%]</th>
<th>Wing 2, no Ribs</th>
<th>e [%]</th>
<th>Wing 2, Ribs</th>
<th>e [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh 1</td>
<td>52.637</td>
<td>1.75</td>
<td>49.707</td>
<td>0.084</td>
<td>408.000</td>
<td>0.0</td>
<td>408.000</td>
<td>0.98</td>
</tr>
<tr>
<td>Mesh 2</td>
<td>53.558</td>
<td>2.50</td>
<td>49.749</td>
<td>0.531</td>
<td>408.000</td>
<td>0.0</td>
<td>412.000</td>
<td>1.94</td>
</tr>
<tr>
<td>Final</td>
<td>54.896</td>
<td>-</td>
<td>50.013</td>
<td>-</td>
<td>408.000</td>
<td>-</td>
<td>404.000</td>
<td>-</td>
</tr>
</tbody>
</table>

As it is possible to check from figures 3.10 and 3.11, the configurations that had ribs needed more nodes because they were more complex geometries. Figure 3.12 shows the need for creating more different regions, when the structure had ribs, to build the geometry’s mesh. Those different regions
were subtitled as it is shown in figure 3.9.

![Mesh for a geometry without ribs](image1)

![Mesh for a geometry with ribs](image2)

Figure 3.12: Influence of the Ribs in the geometry’s mesh

As it is possible to see in figure 3.12, most of the elements were \textit{CQUAD}_4 (quadrilateral plate element connection). However, due to the geometry’s complexity, specially near the trailing edge, this type of elements could not fill all the surface. Therefore, in these regions it was needed to use elements of the type \textit{CTRIA}_3 (triangular plate element connection).

Also, for the aluminium configurations, \textit{Wing 2} (high \textit{AR} wings) have higher values of \text{von Mises} stress. Regrading the composite models, the configurations that have higher values of deformation energy’s density correspond to \textit{Wing 2} (high \textit{AR} wings).

With the meshes established and refined, it was possible to start the structural analysis of the different models. The first one to be performed was the \textit{Static Analysis}.

### 3.3.2 Static Analysis Implementation

In order to reduce the number of variables in this analysis, the load applied in all the wings was the same. The load type applied was a pressure with a constant distribution along the wing’s lower surface and in the positive \(z\) direction. The intensity of the load was determined by the ratio \(\frac{W}{S}\) of the heaviest configuration (where \(W\) is the total aircraft weight and \(S\) the wing area which is the same for all wings analysed) and applied as a pressure to all the models. To understand the behaviour of the models, it was chosen the higher value of \(\frac{W}{S}\). In this way, all the concepts had an ascendant pressure in their lower surface of 4720 \(N/m^2\). Regarding the degrees of freedom, the wings were cantilevered.

The \textit{Static Analysis} was performed in order to obtain the values of the maximum tip displacement \(w_{\text{max}}\) and the maximum stress \(\sigma_{\text{max}}\), for all the models analysed.

After the \textit{Static Analysis} was established, a \textit{Modal Analysis} was performed in order to analyse the first 10 vibration modes.

### 3.3.3 Modal Analysis Implementation

As well as in the \textit{Static Analysis}, in the \textit{Modal Analysis} all the wing models were cantilevered at their root. However, in this type of analysis there was no load applied. This analysis was crucial to understand the materials vibration response and, for that, it was only necessary to establish the boundary conditions without applying any load to the geometry. In this \textit{Modal Analysis} the first 10 vibrations modes were analysed and their natural frequency checked.
After defining the conditions for the Modal Analysis, which were the same for all the configurations, the last structural analysis performed to the geometries was the Linear Buckling Analysis.

### 3.3.4 Buckling Analysis Implementation

The Linear Buckling Analysis was made in a very similar way as the Modal Analysis. Firstly, the boundary conditions were applied, which were the same as the ones assumed for the last two analyses. However, in a different way as in the Modal Analysis, in the Linear Buckling Analysis it was applied a compressive load to the wing’s tip. The intensity of the load chosen to check the response to the critical loads was of $1 \, N$. For all the configurations, the first 10 critical loads were analysed. This third analysis was the last one related to the structural study of the different configurations.

### 3.4 Economic & Environmental Evaluation

The first step was to determine the boundaries to apply on the PBM in order to perform the Economic & Environmental Evaluation. The boundaries of this evaluation were the 3 life cycle phases: production, use and EOL.

With the boundaries established, the resources were the energy, material flow, fuel consumed and material disposal. These resources were determined by the process and the operations models. Table 3.8 shows the resources consumption assumed in each life cycle phase for both financial and environmental models.

<table>
<thead>
<tr>
<th>Phases</th>
<th>Energy</th>
<th>Material Flow</th>
<th>Fuel</th>
<th>Material Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>EOL</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The characterization of the part, such as its area, its thickness and its material is a set of inputs that needs to be taken into account, beyond the annual production volume, the line utilization, the scraps and the reworks.

Figure 2.3 in section 2.1 shows the composition of a line utilization in a 24 hour day. By its analysis, the available time can be given by expression 3.18.

$$T_{available} = 24h - (Maintenance_{OnShift} + Breaks_{unpaid} + Breaks_{paid} + Unplanned_{Downtime}), \quad (3.18)$$

where $T_{available}$ is the available time, $Maintenance_{OnShift}$ is the on shift maintenance, $Breaks_{unpaid}$ is the unpaid breaks, $Breaks_{paid}$ is the paid breaks of the workers and $Unplanned_{Downtime}$ is the unplanned downtime.
During the different stages of the model, errors of production unable some parts to have their parameters according to the project requirements. Therefore, this actual production volume depends not only on the rework, but also on the non-quality scrap and on the initial production volume that is necessary to have at the beginning of the first block to obtain the pretended one at the end of the model. The rework operation has the objective of correcting the parts with defects in order to get quality ones. The scrap and the rework scrap considered on the models are referred to the non-quality parts in the production and in the reworking process, respectively. The model considers also the technical scrap in which the material lost during the various operations is taken into account. For the reworking process, in the composite models, there is another crucial input that is the material required for the rework. This input represents the material needed to correct a defect. All the inputs related to scrap and rework enter the model as percentages.

The actual number of parts, since these are PBM's, is calculated from the end to the beginning of the process. Therefore, the number of parts necessary to manufacture in order to take into account the scrap, in each stage, is given by equation 3.19.

\[ n_{\text{parts}} = \frac{n_{\text{parts}_{i+1}}}{(\%_{\text{rework}} + \%_{\text{passes}} + \%_{\text{reworkPasses}})} \]  

(3.19)

where \( n_{\text{parts}} \) is the number of parts produced, \( \%_{\text{rework}} \) is the percentage of the total material that is reworked in the blocks, \( \%_{\text{passes}} \) is the percentage of the total parts that are in a good condition to go to the next stage of the process and \( \%_{\text{reworkPasses}} \) is the percentage of the total parts that are in a good condition to go to rework in the blocks.

In figure 2.3 in section 2.1, the dependencies of the uptime are shown. In a first step, the time line required needs to be determined by expression 3.20.

\[ T_{\text{req}} = n_{\text{parts}} \cdot CT_i \]  

(3.20)

where \( T_{\text{req}} \) is the required time to do the work and \( CT \) is the cycle time.

Once the required time for a certain line is calculated, the model is able to determine the uptime for that same line with equation 3.21. For that, it is necessary to have the data related to the allocation for a part.

\[ Uptime_i = \frac{T_{\text{req}}}{\%_{\text{Allocation}}}, \]  

(3.21)

where \( Uptime \) is the real time spent on the part's production and \( \%_{\text{Allocation}} \) is the percentage of allocation for a certain part.

Knowing the uptime, from figure 2.3 in section 2.1 is is possible do determine either the downtime or the idle, respectively from equations 3.22 and 3.23.

\[ Downtime_i = \frac{(DpY \cdot 24h) - Uptime_i}{DpY} \]  

(3.22)
Idle\textsubscript{i} = Downtime\textsubscript{i} - (Maintenance\textsubscript{OnShift} + Breaks\textsubscript{unpaid} + Breaks\textsubscript{paid} + Unplanned\textsubscript{Downtime}), \quad (3.23)

where Downtime is the time non-dedicated to the parts’ production, $D_{pY}$ is the days per year in which the company is dedicated to the production, Unplanned\textsubscript{Downtime} is the unplanned downtime and Idle is the time that the workers should dedicate to the production but is wasted by negligence.

Regarding the machine time, there are 3 different possibilities for its determination, according to the different data that it is provided:

- Knowing the value of the machine time, the model introduces it directly on the calculations;
- In composite models, when the machine time is not specified but the number of layers is known, the model obtains the machine time by introducing the layer time directly in the calculations;
- In composite models, when the layer time is not specified but other variables such as part surface area, carbon fibre weight, number of layers and efficiency are known, the model introduces the theoretical lay-up rate, in $kg/hour$, in the calculations.

Regarding the composite models, in this analysis the lay-up rates for ATL and AFP were determined by Lukaszewicz through a comparison of the parameters of the different fibre placement machines [53]. Figure 3.13 shows the lay-up rate for each composite model in function of the surface area.

From figure 3.13 it is possible to obtain the expressions of the lay-up rate in function of the surface area for both models, given in system 3.24.

\[
\begin{align*}
ATL_{\text{lay-up rate}} &= 8.296 \cdot \ln(\text{Part area}) + 10.158 \\
AFP_{\text{lay-up rate}} &= 10.187 \cdot \ln(\text{Part area}) + 19.436
\end{align*}
\]

where $ATL_{\text{lay-up rate}}$ is the ATL lay-up rate, $AFP_{\text{lay-up rate}}$ is the AFP lay-up rate and Part area is the part area.

With the equations in 3.24, knowing the part’s area, the output given will be the lay-up rate for ATL and AFP models. The theoretical layer time is obtained by dividing the weight of the carbon fibre by
the product of the lay-up rate (given by expressions 3.24) with the number of layers. Due to the part’s complexity, it is necessary to add the efficiency to the model to get the corrected layer time. System 3.25 establishes the relations to get the layer time and the corrected layer time [53].

\[
\begin{align*}
    T_{\text{layer}} &= \frac{\text{Weight}_{\text{carbon}}}{\text{rate}_{\text{lay-up}} \cdot n_{\text{layers}}}, \\
    T_{\text{layer\,correct}} &= \frac{T_{\text{layer}}}{\%_{\text{eff}}},
\end{align*}
\]  

(3.25)

where \(T_{\text{layer}}\) is the layer time, \(T_{\text{layer\,correct}}\) is the corrected layer time after the efficiency effect, \(\%_{\text{eff}}\) is the percentage of efficiency, \(n_{\text{layers}}\) is the number of layers, \(\text{Weight}_{\text{carbon}}\) is the carbon fibre weight and \(\text{rate}_{\text{lay-up}}\) is the lay-up rate.

From system 3.25, it is possible to understand that a lower efficiency gives a higher corrected layer time, so it is required more time to lay a single prepreg layer. Thus, having the corrected layer time, the machine time is given by equation 3.26.

\[
T_{\text{machine}} = T_{\text{layer\,correct}} \cdot n_{\text{layers}},
\]

(3.26)

where \(T_{\text{machine}}\) is the machine time.

In the demolding and finishing macro block, the machine time can also be calculated by equation 3.27, when the cutting speed and the cutting perimeter are known data.

\[
T_{\text{machine\,demold}} = \frac{P_c}{v_c},
\]

(3.27)

where \(T_{\text{machine\,demold}}\) is the machine time for demolding and finishing macro block, \(P_c\) is the cutting perimeter and \(v_c\) is the cutting speed.

In the metal’s PBM is possible to obtain a more precise value for the machining cycle time. The alternative is to use the Sandvik formulas given in system 2.2 in subsection 2.3.2 and replacing the value obtained for \(MRR\) in the cycle time formula 2.1.

The resources were, further on traduced into costs on the financial model and into environmental impacts on the environmental model. With the scope presented in figure 3.14 it was possible to establish not only the LCC, but also the LCA for the distinct wing configurations.

![Figure 3.14: PBM Scope](image-url)
3.4.1 Production

The production cost model is different for the composite and the aluminium wings. All the models were divided in several macro blocks. Figure 3.15 presents a process block in which a set of inputs need to be provided to the block in order to allow the calculations to give the outputs of each block.

![Macro Process Block](image)

Figure 3.15: Macro Process Block

Regarding the inputs that need to be provided to each block, they can be either general inputs or specific process inputs. General inputs are the ones that exist in all the macro blocks. These inputs change from company to company and examples of them are presented in table B.1 in section B.0.1. Firstly, it is important to know if a given machine in a specific block is dedicated or not to the single production of that part or if it can also produce other parts. It is also crucial to know the number of workers that are involved in a certain stage/block. Regarding the consumables, they depend on the units used per hour and in the cost of each one.

The composite production models (ATL and AFP) follow the same stages. The first stage is the reception check and storage. This block aggregates the verification of the material after its arrival at the company and the type of storage required to guarantee that the prepeg's properties are maintained. After that, a second process may start its function. Here, the prepeg rolls are prepared and clear for the application of the cooper are glass fibre layers. The third stage, in which the fibre placement happens, is the main difference between these 2 composite PBM's, since its operation requires different machines. Afterwards, the fourth step of the process begins and the glass fibre is applied. After this second application of glass fibre, the part is placed in the autoclave to be cured, on the fifth stage of the model. Step number six of this composite model flowchart is the part's demoulding for final adjustments. The last macro block is when the part goes to the NDT (Non-Destructive Tests) for the final operations. In most of the blocks is produced scrap material and some inappropriate parts that may suffer a rework. The inputs of each block for both ATL and AFP models are barely the same. Regarding the mould information, it contains:

- number of moulds;
- mould's cost;
- time to prepare the mould.

There are particular inputs for some of the macro blocks, such as the cutting perimeter and speed in the demolding and finishing block. Material information, part dimensions and percentages of scrap and rework are also inputs considered in the models. The composite material has a total thickness given by the number of layers and the layer thickness. The part's surface area is an input that is characterized by its degree of complexity.
The scrap price, the material cost per square meter, the material's surface area and the areal weight are required inputs for the model. During the whole model, 3 different materials are used:

- glass fibre;
- carbon fibre prepreg;
- copper.

The carbon fibre rolls' inputs are the tape’s length and width. These variables assume different values for ATL and AFP.

In both composite models, there are no costs related to consumables considered as an individual variable cost. The consumables' cost related to the mould is attached to the material cost. The costs for the composite models are shown in table 3.9

<table>
<thead>
<tr>
<th>Fixed Costs</th>
<th>Variable Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>Material Cost</td>
</tr>
<tr>
<td>Tooling Cost</td>
<td>Scrap Cost</td>
</tr>
<tr>
<td>Fixed Overhead Cost</td>
<td>Labour Cost</td>
</tr>
<tr>
<td>Building Cost</td>
<td>Energy Cost</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>-</td>
</tr>
</tbody>
</table>

For the fixed costs, the investment is annualised. The initial cost is divided into a set of different payments, with an opportunity cost of material (in this case it was considered 15%), paid during the life of the product (machine, equipment, tool or building). This relation is expressed in equation 3.28.

\[
Fixed_{Cost,i} = I_i \cdot \frac{(1 + r)^n_j \cdot r}{(1 + r)^n_j - 1},
\]  
(3.28)

where \( Fixed_{Cost} \) is the fixed cost, \( I \) is the initial investment, \( r \) is the opportunity cost of capital and \( n \) is the product's life.

The main machine cost is determined by equation 3.29. For this calculation it is necessary to take into account the percentage of line allocation for a certain part in a given process stage.

\[
Cost_{Machine} = Cost_{acquisition} \cdot n_{machine} \cdot \%Allocation,
\]  
(3.29)

where \( Cost_{Machine} \) is the cost of all the machines bought, \( Cost_{acquisition} \) is the cost of a single machine or tool and \( n_{machine} \) is the number of machines bought.

For the total tooling cost, since the tools are considered as dedicated to one particular task, there is no need to have a percentage of allocation for them. The models calculate the tooling cost by expression 3.30.

\[
Cost_{Tool} = Cost_{acquisition} \cdot n_{tool},
\]  
(3.30)

where \( Cost_{Tool} \) is the cost of all the tools bought and \( n_{tool} \) is the number of tools bought.
The diagrams of the machine and tool costs are shown in figure 3.16.

The building costs require a significant investment. The machines and tools occupy physical space. Also, the building’s life enters in the annuity formula of this fixed cost given in expression 3.28. As well as the space required for the machines and tools, the idle space needs to be translated into euros, because it is a cost that enters in the macro cost block of the building cost, calculated through equation 3.31.

\[
Cost_{Building} = (1 + \%_{IdleSpace}) \cdot Area_{req} \cdot Cost_{construction} \cdot \%_{Allocation},
\]

where \(Cost_{Building}\) is the total investment in the building, \(\%_{IdleSpace}\) is the percentage of space that should be dedicated to the production but is wasted by negligence, \(Area_{req}\) is the area required for the machines and \(Cost_{construction}\) is the building’s construction expenses.

In figure 3.17 is shown the building cost diagram.

Both maintenance or overhead costs are determined as a percentage of other costs. In this model it was considered as 10%. Regarding the maintenance, this cost is related to the machines’ inspection and repairing. Its calculation is made through expression 3.32.

\[
Cost_{Maintenance} = Cost_{Machine} \cdot \%_{Maintenance},
\]

where \(Cost_{Maintenance}\) is the maintenance cost and \(\%_{Maintenance}\) is the percentage of maintenance required for a certain machine.

The overhead costs represent the indirect costs to the production and are given by equation 3.33.

\[
Cost_{Overhead} = (Cost_{Machine} + Cost_{Building} + Cost_{Tool} + Cost_{Maintenance}) \cdot \%_{Overhead},
\]
where \( \text{Cost}_{\text{Overhead}} \) is the indirect costs to the production and \( \%_{\text{Overhead}} \) is the percentage of overhead in the model.

The variable costs are the ones that depend directly on the production volume. Consumable costs are variable costs and an example of them is the paint that is used and that will be needed to be replaced when the stock reaches its end. To determine the consumables cost, the units of consumables, their cost per unit and the required line time are inputs needed to provide to the model. Expression 3.34 gives the equation that enables the model to calculate the consumables cost.

\[
\text{Cost}_{\text{consumables}} = \text{Consumables cost/unit} \cdot n_{\text{consumables}} \cdot T_{\text{req}},
\]

where \( \text{Cost}_{\text{consumables}} \) is the consumables cost, \( \text{Consumables cost/unit} \) is the cost of a unit of consumables and \( n_{\text{consumables}} \) is the number of consumables used.

The diagram of the consumable's cost is shown in figure 3.18.

\[
\text{Labour cost} = T_{\text{req}} \cdot n_{\text{workers}} \cdot \%_{\text{dedication}} \cdot \text{wage},
\]

where \( \text{Labour cost} \) is the labour cost, \( n_{\text{workers}} \) is the number of workers necessary to do the task, \( \%_{\text{dedication}} \) is the workers' dedication, in percentage, to perform a certain task and \( \text{wage} \) is the worker's salary per hour.

In this particular analysis, the labour costs only consider the direct workers. All the indirect workers will be taken into account in the overhead costs. The diagram of the labour costs is shown in figure 3.19.

Regarding the energy cost, it is possible to determine it by equation 3.36. It is crucial to know the annual production time, as well as the required time.

\[
\text{Energy cost} = T_{\text{req}} \cdot P_{\text{consumption}} \cdot \text{Unit}_{\text{Energy cost}},
\]

where \( \text{Energy cost} \) is the energy cost, \( P_{\text{consumption}} \) is the power consumption and \( \text{Unit}_{\text{Energy cost}} \) is the unitary energy cost.

The diagram of the energy cost and its inputs is shown in figure 3.20.
The material costs are determined by using the system of equations 3.37. From system 3.37 it is possible to check that the number of layers is an input for the carbon fibres, but not for the copper and glass fibre. This happens because it was made an assumption in order to simplify the calculations to place only 1 layer of each material (copper and glass fibre) for each process macro block. Also, from system 3.37, the material’s cost also depends on the cost of reworking some of the material.

\[
\begin{align*}
\text{Cost}_{\text{rework material}} &= \%_{\text{rework}} \cdot \text{Material}_{\text{req rework}} \cdot n_{\text{parts}} \cdot n_{\text{layers}} \cdot \text{Cost}_{\text{euro/sqm}} \cdot \text{Mat}_{\text{area}} \\
\text{Mat}_{\text{cost}}(\text{copper + glass}) &= (\text{Cost}_{\text{euro/sqm}} \cdot \text{Mat}_{\text{area}} \cdot n_{\text{parts}}) + \text{Cost}_{\text{rework material}} \\
\text{Mat}_{\text{cost}}(\text{carbon}) &= (\text{Cost}_{\text{euro/sqm}} \cdot \text{Mat}_{\text{area}} \cdot n_{\text{layers}} \cdot n_{\text{parts}}) + \text{Cost}_{\text{rework material}} 
\end{align*}
\]  

(3.37)

where \(\text{Cost}_{\text{rework material}}\) is the cost related to the material rework, \(\text{Cost}_{\text{euro/sqm}}\) is the material cost per square metre, \(\text{Mat}_{\text{area}}\) is the area of material bought, \(\text{Mat}_{\text{cost}}(\text{copper + glass})\) is the cost of the copper and glass fibre material and \(\text{Mat}_{\text{cost}}(\text{carbon})\) is the cost of the carbon fibre material.

Regarding the fibre placement macro block, the material cost in this operation depends on the consumables cost regarding the mould. System 3.38 shows the relations established in order to get these costs.

\[
\begin{align*}
\text{Cost}_{\text{consumables}} &= \text{Cost}_{\text{consumables/sqm}} \cdot \text{Part}_{\text{area}} \\
\text{Mat}_{\text{cost}}(\text{block fibre place}) &= \text{Mat}_{\text{cost}}(\text{carbon}) + \text{Cost}_{\text{consumables}} 
\end{align*}
\]  

(3.38)

where \(\text{Mat}_{\text{cost}}(\text{block fibre place})\) is the material cost in the fibre placement block.

In these models, the macro blocks have scrap material. In metal models, the scrap is considered as
a revenue, because it is possible to be reused in a very simple way. However, for the composite models, scrap material is considered as a cost. The scrap that results from the copper is covered in epoxy resin so, it is not possible to reuse it. For the composite models, the areal weight is an input that needs to be taken into account. Equation 3.39 gives the total scrap cost, for a certain block, in the composite’s models.

\[
\text{Cost}_{\text{scrap}} = \text{Areal weight} \cdot \text{Mat area} \cdot n_{\text{layers}} \cdot n_{\text{parts}} \cdot \text{Cost}_{\text{scrap kg}} \cdot (\%_{\text{technical scrap}} + \%_{\text{quality scrap}} + \%_{\text{rework}} \cdot \%_{\text{rework scrap}})
\]

(3.39)

where \( \text{Cost}_{\text{scrap}} \) is the scrap cost for the composite models, \( \text{Areal weight} \) is the areal weight, \( \text{Cost}_{\text{scrap kg}} \) is the scrap cost per kilogram for the composite models, \( \%_{\text{technical scrap}} \) is the percentage of technical scrap, \( \%_{\text{quality scrap}} \) is the percentage of quality scrap and \( \%_{\text{rework scrap}} \) is the percentage of reworked scrap.

With the composite’s production cost models implemented, the metal’s model follows a very similar methodology.

In a very similar way as in the composite’s PBCM, the metal’s PBCM was performed in a block’s diagram sequence with different 7 stages for the part’s production in the aluminium. Scrap material will appear in all the macro blocks. In a particular analysis of blocks 2 and 4, respectively, machining and shot peening, the reworking processes are made on the same machine. Therefore, the part will return to the beginning of the same macro block. On the other hand, for macro block 5, surface treatment and painting, the rework is done outside the block, since it is performed in another machine.

The fixed costs, the labour costs and the energy costs of this model are determined in the same way as in the composites’ models. However, part of the variable costs related to the material costs are determined in a distinct way, since the manufacture of composites is different from the metal’s machining. Material cost is dependent of the production volume, so it is a variable cost, given by equation 3.40.

\[
\text{Mat}_{\text{cost}}(\text{aluminium}) = (\text{Cost}_{\text{euro/kg}} \cdot \text{Weight}_{\text{RM}} \cdot n_{\text{parts}}) - \text{Cost}_{\text{scrap metal}},
\]

(3.40)

where \( \text{Mat}_{\text{cost}}(\text{aluminium}) \) is the cost of the aluminium parts, \( \text{Cost}_{\text{euro/kg}} \) is the material cost per kilogram, \( \text{Weight}_{\text{RM}} \) is the raw material weight and \( \text{Cost}_{\text{scrap metal}} \) is the scrap cost for the metal models.

In the middle there are some calculations needed, which are presented on system 3.41.

\[
\begin{align*}
\text{Part volume} &= \text{Part area} \cdot \text{Part height} \\
\text{RM}_{\text{volume}i} &= \frac{\text{RM}_{\text{volume}i+1}}{1-\%_{\text{technical scrap}}} \\
\text{Weight}_{\text{RM}i} &= \text{RM}_{\text{volume}i} \cdot \rho_{\text{mat}} \\
\text{Cost}_{\text{scrap metal}} &= \text{Weight}_{\text{RM}i} \cdot n_{\text{parts}} \cdot \text{Cost}_{\text{scrap kg}} \cdot (\%_{\text{technical scrap}} + \%_{\text{quality scrap}} + \%_{\text{rework}} \cdot \%_{\text{rework scrap}})
\end{align*}
\]

(3.41)

where \( \text{Part volume} \) is the part’s volume, \( \text{Part height} \) is the part’s height and \( \text{RM}_{\text{volume}i} \) is the raw material’s
For a better understanding of the inputs and the calculations needed to determine the material costs for the metal’s PBM, figure 3.21 shows the material cost’s diagram.

![Figure 3.21: Material Costs Diagram for Aluminium Model](image)

In a similar way to the LCC’s production phase, for the part’s manufacture scope in the LCA, the same resources (material flow and energy) were considered and the same stages were taken into account. After the part’s manufacture was completed, its utilization during its useful life was transformed into environmental impact and finishing at the part’s EOL. In this way, a whole cradle-to-grave analysis was performed for the different configurations.

The main goal of the LCA’s application on this thesis was to get a clear comparison between the different configurations’ environmental impact. The software used to transform those resources into environmental impacts was SimaPro, through the ReCiPe method. The functional unit adopted in this analysis was the weight of fuel consumed in the wings total life-cycle due to the weight of the 2 aircraft wings. In order to simplify the comparison process, in the production were only considered metal and composite PBM’s and the difference between ATL and AFP was not applied. The values assumed for the composite’s production were the ones provided by the ATL model in the LCC. However, if the results obtained by the AFP were considered instead of the ones given by the ATL model, the values would be very similar since the resources needed for the part’s production are barely the same.

3.4.2 Use

In order to determine an approximation of the total costs and environmental impacts During the aircraft’s useful life with the different wing configurations, it was necessary to determine the fuel consumption for all the flights made. For that, some assumptions had to be made in order to have the same boundary conditions to enable a better comparison:

- The only flight mode considered was the cruise level;
- The cruise speed adopted was the one use in the aerodynamic analysis: $V_{cr} = 230, 15 \text{ m/s}$;
- A thrust specific fuel consumption in the cruise level of $C_{TSFC} = 0, 4 \text{ h}^{-1}$;
• A flight range of $R = 2000 \text{ nm}$;

• An initial fuel weight given by EMBRAER of $W_{\text{fuel}} = 14000 \text{ kg}$;

• A total distance travelled in the aircraft’s useful life of $105 \cdot 10^6 \text{ km}$;

• Fuel data considering AVGAS 100LL [54] for Cascais Airport: $\text{Cost}_{\text{fuel}} = 1,51 \text{ euros/L}$ and $\rho_{\text{fuel}} = 0,72 \text{ kg/L}$;

• The use of the different configurations in an aircraft is directly dependent of the $\frac{L}{D}$ factor by the Breguet’s Equation, in expression 3.17, so by the aerodynamic analysis there would be only 2 different values for the utilization cost.

With the determination of the fuel consumption regarding the useful life of the configurations, it was possible to determine the costs and the environmental impacts of the distinct concepts in this life cycle phase.

For both LCC and LCA analyses, the same boundaries were applied. On the use phase the blocks of fuel consumed establish the connection between the LCC and the LCA, enabling the possibility of generating a financial model and an environmental model from the operations model. To transform the resources’ consumption into environmental impacts was used, again, the software SimaPro through the method ReCiPe.

3.4.3 End-of-Life

Usually, metals keep their mechanical properties after recycling processes in a very easy way. Therefore, either in the LCC analysis or in the LCA analysis, recycling was the EOL process taken into account for the wing configurations made in aluminium [55].

On the other hand, composites are a group of materials in which recycling is not used so much because it is very hard to keep their mechanical properties. In the aeronautical industry, incineration and landfilling are the historically most suitable options for composite part’s EOL [56].

The material composition affects directly the environmental impact of the parts production and also its EOL. Different processes will be applied to the distinct materials due to their reuse and transformation capabilities:

• metals: recycling may be used, to have material to other industries, since metals are easier to machine and to mould;

• composites: scrap usually suffers incineration since this composite is built-up from 3 different materials and it is more difficult to perform rework. Also, recycling is not usually performed in composites [57];

Regarding the aluminium wings, the cost of their recycling was assumed to be only directed to the energy consumed by the machine, since it is the largest fraction of their total EOL costs. The cost of recycling an aluminium part was assumed to be at about 30% of its production cost [58]. Thus, knowing
the production cost of each configuration, it was possible to determine the EOL costs for the aluminium wings.

For the composite wings, Boeing informs that the composite part's recycling would cost at about 70% of the initial production cost. As it was already exposed, the EOL alternative used for these configurations is the incineration. In this process is produced 15 $MJ/kg$ of energy. The energy spent on the combustion is insignificant when compared to the energy produced by this process. Therefore, for the composite wings, the EOL costs due to incineration were considered null [59].

For both LCC and LCA analyses, the same boundaries were applied. On the EOL phase the energy consumed on the final disposal processes and the parts’ material establish the connection between the LCC and the LCA. Also, in order to transform the resources’ consumption into environmental impacts was used the software SimaPro through the method ReCiPe.
Chapter 4

Results

4.1 Aerodynamic Analysis

In section 3.2 it is explained the methodology established by Corke [51], in chapter 4 (Main Wing Design), and followed in this thesis.

In order to understand the lift polar plot shown in figure 3.8 it was crucial to relate it with the airfoil's curvature. Since the root airfoil of both concepts had positive curvature, it verified a positive $C_{L\alpha=0}$ which can be seen in plot 3.8.

In this analysis we are dealing with two wings with the same airfoils but with a different $AR$. According to the lift polar equation 3.14 and its plot (see figure 3.8), the graphs of the two concepts cross in $C_{L\alpha=0} = 0.2131268$. However, the higher aspect ratio a wing has, the higher will be the lift coefficient $c_L$ for the same angle of attack $\alpha$, as figure 4.1 shows.

![Figure 4.1: Relation between the Lift Polar and the wing's AR](image)

Since the case study had cruise level conditions, a low angle of attack of $0.5^\circ$ was assumed for both wings. Substituting this value in the lift polar of each wing (system 3.14) the result was the lift coefficient of each concept, for this angle of attack (system 4.1).

\[
\begin{align*}
C_{L_{wing1}} &= 0.265 \\
C_{L_{wing2}} &= 0.274
\end{align*}
\]

With the lift coefficient's determination for both external configurations by replacing its values in the drag polar system 3.11, the drag coefficients for this angle of attack were determined (4.2).
\[
\begin{align*}
C_{D_{\text{wing}1}} &= 0.01086 \\
C_{D_{\text{wing}2}} &= 0.00956
\end{align*}
\] (4.2)

With the lift and drag coefficients determined, and the dimensions and external conditions established, the loads applied to the wing were calculated by the equations shown in 4.3.

\[
\begin{align*}
L &= C_L \cdot \frac{1}{2} \cdot \rho_{cr} \cdot S \cdot V_{cr}^2 \\
D &= C_D \cdot \frac{1}{2} \cdot \rho_{cr} \cdot S \cdot V_{cr}^2
\end{align*}
\] (4.3)

where \( L \) is the lift load and \( D \) is the drag load.

The pitching moment around the gravity centre was calculated through the lift load applied at the aerodynamic centre by the equation 3.16. In table 4.1 are presented the values of the loads and the moment applied in each wing configuration.

<table>
<thead>
<tr>
<th>Table 4.1: Wing Loads and Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>( L ) [N]</td>
</tr>
<tr>
<td>( D ) [N]</td>
</tr>
<tr>
<td>( M ) [Nm]</td>
</tr>
</tbody>
</table>

Through equation 4.4 and knowing the moment around the wing’s centre of gravity, it was possible to determine the moment coefficient \( C_M \).

\[
C_M = \frac{M}{\frac{1}{2} \cdot \rho_{cr} \cdot S \cdot V_{cr}^2 \cdot c}
\] (4.4)

For a better comparison between the two concepts, apart from the parameter \( C_M \), \( \frac{L}{D} \) was also crucial to get. In table 4.2 are shown these two coefficients for both wing configurations.

<table>
<thead>
<tr>
<th>Table 4.2: Moment Coefficient and Lift to Drag ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>( C_M )</td>
</tr>
<tr>
<td>( \frac{L}{D} )</td>
</tr>
</tbody>
</table>

The performance of the wing depends a lot on its \( \frac{L}{D} \), as it was possible to understand at the end of section 3.2 with the Breguet range expression (see equation 3.17). An increase of the wing’s aspect ratio for the same airfoil area provided a decrease on the induced drag. However, the Reynolds number was lower and conduced to higher viscous drag values. For low angles of attack (taking as an example the one assumed for this cruise mode, \( \alpha = 0.5^\circ \)), the lift over drag ratio was higher for the wing with higher aspect ratio. Taking into account Breguet’s equation, an aircraft with a higher \( \frac{L}{D} \) requires less fuel to fly the same flight ranges, considering the same cruise speed and the same thrust-specific fuel consumption. From figure 4.2, it is possible to check that the high AR wing had a higher \( \frac{L}{D} \) ratio than the original configuration, for a positive \( \alpha \).
However, to get the maximum $\frac{L}{D}$ for the original configuration, cruise level should be established at $\alpha = 1.6^\circ$ and for the high $AR$ wing, the maximum $\frac{L}{D}$ needed to have a higher angle of attack ($\alpha = 2.8^\circ$). Flying with a moderate angle of attack, the shock waves' phenomena on the wings increases its intensity, raising the drag load's value and conducing to a lower lift over drag ratio.

As the wings were operating at a cruise level in this analysis, the angle of attack assumed had a low value: $\alpha = 0.5^\circ$.

For this $\alpha$, the percentage growth of $\frac{L}{D}$ given by expression 4.5 was 17.5%.

$$\left( \frac{\Delta \frac{L}{D}}{\%} \right) = \frac{\left( \frac{L}{D} \right)_{highAR} - \left( \frac{L}{D} \right)_{original}}{\left( \frac{L}{D} \right)_{original}} \cdot 100\%, \quad (4.5)$$

where $\left( \frac{\Delta \frac{L}{D}}{\%} \right)$ is the percentage growth of $\frac{L}{D}$, $\left( \frac{L}{D} \right)_{highAR}$ is the lift to drag ratio for the high $AR$ wing and $\left( \frac{L}{D} \right)_{original}$ is the lift to drag ratio for the original wing.

Since the position of the gravity centre assumed was, for a very stable stage, $x_{CG} = 0.125 \cdot c$, a possible increase of $\alpha$ would increase the lift load in the main wing, increasing the lift coefficient and, consequently, decreasing the pitching moment of the aircraft, since it had negative values. However, the original wing had a better value of $C_M$ than the high $AR$ one. The closer this value is to zero, the lower will be the load on the horizontal stabilizer to balance the aircraft [61], as it is possible to see in figure 4.3.

As it was expected, the wings with a higher aspect ratio have bigger values of $\frac{L}{D}$ ratio. The higher this ratio is, the better will be the wing’s performance. In this way, for the same root airfoil, high aspect ratio wings conduce to a lower consumption of fuel blocks as it will be possible to check out from Breguet’s equation in the cost’s analysis. Regarding the $C_M$, the closer this value is to 0, more stabilized is the aircraft, since the load on the horizontal tail is lower. The increase of the wing’s aspect ratio, moves the value of $C_M$ away from 0. In this way, since the original wing had a lower aspect ratio, its $C_M$ was closer
Figure 4.3: Aircraft Loads and Moments [62]

to 0, making this wing more stabilized than the high aspect ratio wing. With the aerodynamic results determined, it is time to verify the mechanical behaviour of the different configurations in a structural way.

4.2 Structural Results

As it was explained in section 3.3, the different configurations were submitted to the same boundary conditions for each analysis and for the same load regarding the Static Analysis and the Linear Buckling Analysis. This assumption reduced the variables in the comparison and made the analyses more clear in a qualitative way.

The first analysis performed was the Static one.

4.2.1 Static Analysis

In subsection 3.3.2 the conditions for this analysis were defined. From those boundary conditions and pressure applied, the interesting results to analyse in this thesis were the maximum tip displacement, $w_{\text{max}}$, and the maximum stress on the structure $\sigma_{\text{max}}$. The same load as in the aerodynamic analysis was applied in all the different wing configurations. For the 8 different configurations, their mechanical behaviour in the static analysis gave the results presented in table 4.3.

<table>
<thead>
<tr>
<th>Concept</th>
<th>$\sigma_{\text{max}}$ [MPa]</th>
<th>$w_{\text{max}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs, IM7</td>
<td>277.47</td>
<td>553.43</td>
</tr>
<tr>
<td>Wing 1, no ribs, A6061</td>
<td>113.97</td>
<td>312.68</td>
</tr>
<tr>
<td>Wing 1, ribs, IM7</td>
<td>250.04</td>
<td>547.77</td>
</tr>
<tr>
<td>Wing 1, ribs, A6061</td>
<td>101.32</td>
<td>309.58</td>
</tr>
<tr>
<td>Wing 2, no ribs, IM7</td>
<td>556.13</td>
<td>4117.14</td>
</tr>
<tr>
<td>Wing 2, no ribs, A6061</td>
<td>231.80</td>
<td>2326.93</td>
</tr>
<tr>
<td>Wing 2, ribs, IM7</td>
<td>231.80</td>
<td>2326.93</td>
</tr>
<tr>
<td>Wing 2, ribs, A6061</td>
<td>561.75</td>
<td>4096.56</td>
</tr>
</tbody>
</table>

The wings were cantilevered at their roots and an ascendant pressure was applied on their lower surface. In order to check this system's consequence, it was analysed the wing's tip displacement and
its maximum stress (check figure 4.4 for an example, this result belongs to the original wing, without ribs, made of aluminium A6061). The other results can be seen in annexe figures A.1 and A.2.

![Static Analysis](image1.png)

![Static Analysis](image2.png)

Figure 4.4: Static Analysis for the original wing, without ribs, made in aluminium A6061

As it is possible to check from table 4.3, the first interpretation that these results provide is the fact that, for this loading type and intensity, the composite configurations had higher values of maximum stress and maximum tip displacement.

Multiple factors related to the composite structure may be behind this result, such as:

- Layer’s orientation;
- Number of layers;
- Layer’s thickness.

For the original wing configuration, the introduction of ribs reduced the maximum tip displacement and the maximum stress for both materials. Although the decrease was not very significant, it is important to understand the structural resistance that this internal components gave to the wing. The type of loading and its distribution was not the most indicated one to check the importance of the ribs in a wing’s structure. However, their structural improvement was shown in the results.

From table 4.3 it is possible to check that the high aspect ratio wing configurations had bigger values of maximum tip displacement. This happens due to the fact that, for the same wing area and the same load applied, these configurations were longer and narrower. The introduction of ribs in the internal configuration reduced the maximum tip displacement since these components gave an extra resistance to the body. However, the maximum stress on the configurations with ribs was slightly higher because it happened on these structural components. Regarding the material, it was expected to have lower values of maximum stress and maximum tip displacement for the composite wings, since the same load is applied to the different wings. However, from table 4.3 it is possible to see that this did not happen.

Multiple factors may be behind this fact. Either the fibres did not have the suitable orientation or even because the layers’ thickness was not the most indicated regarding this load type. The composite’s domain has a very large spectrum and the fact that this composite was not the most indicated for this specific case study, others could be and a good answer of their structural behaviour could be expected.

With the Static Analysis results obtained, the Modal Analysis was performed and interpreted.
4.2.2 Modal Analysis

The conditions to perform this analysis were expressed in subsection 3.3.3. The results taken from this analysis were the first 10 vibration modes. Table 4.4 shows the natural frequencies for the first 10 vibration modes of each of the 8 configurations analysed. One can note that the fundamental natural frequency, corresponding to the first flap bending (out-of-wing plane bending) decreased as the aspect ratio increases. From table 4.4 it is possible to check that for the first vibration modes, high aspect ratio wings had a behaviour similar to a beam and the original external configuration wings behaved similarly to a plaque.

Table 4.4: Modal Analysis

<table>
<thead>
<tr>
<th>Concept</th>
<th>1 [Hz]</th>
<th>2 [Hz]</th>
<th>3 [Hz]</th>
<th>4 [Hz]</th>
<th>5 [Hz]</th>
<th>6 [Hz]</th>
<th>7 [Hz]</th>
<th>8 [Hz]</th>
<th>9 [Hz]</th>
<th>10 [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs, IM7</td>
<td>3.66</td>
<td>9.79</td>
<td>12.38</td>
<td>13.01</td>
<td>14.07</td>
<td>14.81</td>
<td>15.55</td>
<td>16.84</td>
<td>18.47</td>
<td>19.10</td>
</tr>
<tr>
<td>Wing 1, no ribs, A6061</td>
<td>3.59</td>
<td>9.96</td>
<td>12.35</td>
<td>12.83</td>
<td>14.30</td>
<td>15.05</td>
<td>15.66</td>
<td>17.08</td>
<td>18.81</td>
<td>19.30</td>
</tr>
<tr>
<td>Wing 1, ribs, IM7</td>
<td>3.62</td>
<td>13.35</td>
<td>21.00</td>
<td>23.05</td>
<td>24.96</td>
<td>25.72</td>
<td>26.33</td>
<td>28.20</td>
<td>29.78</td>
<td>30.83</td>
</tr>
<tr>
<td>Wing 1, ribs, A6061</td>
<td>3.55</td>
<td>13.08</td>
<td>20.58</td>
<td>23.50</td>
<td>25.42</td>
<td>25.48</td>
<td>26.50</td>
<td>28.08</td>
<td>30.08</td>
<td>31.15</td>
</tr>
<tr>
<td>Wing 2, no ribs, IM7</td>
<td>3.48</td>
<td>9.46</td>
<td>10.82</td>
<td>11.56</td>
<td>13.77</td>
<td>15.25</td>
<td>16.03</td>
<td>18.27</td>
<td>20.36</td>
<td>20.59</td>
</tr>
<tr>
<td>Wing 2, no ribs, A6061</td>
<td>3.41</td>
<td>9.27</td>
<td>11.01</td>
<td>11.81</td>
<td>13.97</td>
<td>15.34</td>
<td>16.30</td>
<td>18.18</td>
<td>20.22</td>
<td>20.85</td>
</tr>
<tr>
<td>Wing 2, ribs, A6061</td>
<td>1.31</td>
<td>4.99</td>
<td>7.95</td>
<td>11.19</td>
<td>18.88</td>
<td>19.32</td>
<td>21.57</td>
<td>23.22</td>
<td>26.76</td>
<td>27.66</td>
</tr>
</tbody>
</table>

The configurations had modes that show a behaviour similar to a beam vibration mode and others that had a plaque vibration mode. In figure 4.5 it is possible to see the different behaviour of the vibration modes for the same geometry.

![Mode 1 - beam mode](image1)

![Mode 7 - plaque mode](image2)

Figure 4.5: Modal Analysis for the original wing, without ribs, made in aluminium A6061

The images 4.5 of the vibration modes show how the structure would vibrate in a scaled way, otherwise it would not be possible to understand their behaviour against certain natural frequencies. All the 10 vibration modes for the 8 different concepts are in annexe figures A.3 to A.10.

The increase of a wing's aspect ratio, maintaining the wing area, turned the wing into a narrower and longer configuration. Thus, wings with higher aspect ratio tend to look and behave as beams. Wings with lower aspect ratio are shorter larger, looking and behaving more as plaques. The modal analysis reflected this behaviours.

The last structural analysis to be performed to the concepts was the Linear Buckling Analysis.
4.2.3 Buckling Analysis

In subsection 3.3.4 were defined the conditions and the load involved in the Linear Buckling Analysis. This analysis gave the values of the critical loads to the structure. Table 4.5 presents the 10 first critical loads for the 8 different configurations.

Table 4.5: Buckling Analysis

<table>
<thead>
<tr>
<th>Concept</th>
<th>1 [kN]</th>
<th>2 [kN]</th>
<th>3 [kN]</th>
<th>4 [kN]</th>
<th>5 [kN]</th>
<th>6 [kN]</th>
<th>7 [kN]</th>
<th>8 [kN]</th>
<th>9 [kN]</th>
<th>10 [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs, IM7</td>
<td>133.3</td>
<td>133.4</td>
<td>144.0</td>
<td>144.3</td>
<td>153.7</td>
<td>154.0</td>
<td>163.6</td>
<td>164.0</td>
<td>165.7</td>
<td>166.3</td>
</tr>
<tr>
<td>Wing 1, no ribs, A6061</td>
<td>253.2</td>
<td>253.4</td>
<td>273.7</td>
<td>274.3</td>
<td>292.8</td>
<td>293.6</td>
<td>312.2</td>
<td>312.5</td>
<td>316.8</td>
<td>318.8</td>
</tr>
<tr>
<td>Wing 1, ribs, IM7</td>
<td>152.9</td>
<td>155.7</td>
<td>161.2</td>
<td>163.0</td>
<td>169.3</td>
<td>172.0</td>
<td>180.7</td>
<td>186.4</td>
<td>190.2</td>
<td>191.0</td>
</tr>
<tr>
<td>Wing 1, ribs, A6061</td>
<td>291.5</td>
<td>296.7</td>
<td>307.3</td>
<td>310.1</td>
<td>323.2</td>
<td>326.6</td>
<td>343.7</td>
<td>357.1</td>
<td>362.6</td>
<td>365.6</td>
</tr>
<tr>
<td>Wing 2, no ribs, IM7</td>
<td>118.4</td>
<td>118.5</td>
<td>121.4</td>
<td>121.5</td>
<td>125.2</td>
<td>125.4</td>
<td>130.0</td>
<td>130.4</td>
<td>132.4</td>
<td>135.8</td>
</tr>
<tr>
<td>Wing 2, no ribs, A6061</td>
<td>226.9</td>
<td>227.0</td>
<td>232.6</td>
<td>232.7</td>
<td>234.4</td>
<td>240.4</td>
<td>240.5</td>
<td>250.3</td>
<td>250.5</td>
<td>262.4</td>
</tr>
<tr>
<td>Wing 2, ribs, IM7</td>
<td>126.4</td>
<td>127.0</td>
<td>127.9</td>
<td>128.5</td>
<td>129.5</td>
<td>129.6</td>
<td>132.5</td>
<td>133.0</td>
<td>133.2</td>
<td>143.5</td>
</tr>
<tr>
<td>Wing 2, ribs, A6061</td>
<td>235.5</td>
<td>240.3</td>
<td>242.4</td>
<td>243.9</td>
<td>244.3</td>
<td>245.0</td>
<td>246.5</td>
<td>250.7</td>
<td>251.6</td>
<td>275.5</td>
</tr>
</tbody>
</table>

As well as in the Modal Analysis, in the Linear Buckling Analysis, there were some modes of the same geometry that reveal a beam critical behaviour and others that reveal a plaque buckling response. Figure 4.6 shows, for the same configuration, two different critical behaviours.

Figure 4.6: Linear Buckling Analysis for the high AR wing, with ribs, made in aluminium A6061

From table 4.5 it is possible to understand that the critical loads started, for all the configurations, above 100 kN. Also, the critical loads were lower for the configurations made in the composite IM7 than for the ones in aluminium A6061.

Comparing the different AR concepts, the original wings had higher values of buckling loads than the higher AR wings. Also, the introduction of ribs in the structures increased the values of the critical loads.

With the last structural analysis performed, it is necessary to start the study of the configurations’ economic and environmental evaluation not only in terms of their production, but also regarding all their life use and their EOL.

4.3 Economic & Environmental Evaluation

As table 3.8 exposes, for the economic and the environmental evaluation, each life cycle phase has its own resources consumption. The boundaries of these analyses were the 3 life cycle phases: production,
use and EOL. In the production phase, the resources consumed taken into account were the energy and the material flow. In the use phase, the only resource considered was the fuel blocks consumption. In the EOL phase, both quantity of material disposed and energy consumption were the resources considered.

4.3.1 Process Model - Inventory

Production - Inventory

The boundaries applied in the production phase behaved in a different way in each PBM and produced different impacts in terms of costs (financial model) and in terms of environment (environmental model) for each wing configuration. The geometries studied were explained in a more detailed way in subsection 3.1.1 and the materials used were characterized in subsection 3.1.2 of this thesis.

In both composite PBM’s (ATL and AFP) all the stages were considered the same. From figure 4.7 it is possible to check that the number of parts for each external configuration in both models had the same values for all the process line’s stages, entering material in the process for the production of 261,0 parts and ending with material for the expected 100 parts.

![Figure 4.7: Flow of the composite parts along the process](image)

With the information provided by figure 4.7 it was possible to determine the carbon fibre that entered and left each stage of the process. Also, for ATL and AFP processes, the 4 different wing configurations required specific mass values to enter the models in order to have the projected weights. Figures 4.8 and 4.9 show the material flow and the macro-block that summarizes each composite PBM.

A significant difference between the 2 PBM for composites analysed was exposed in the scrap information. In stage number 3, fibre placement, the technical scrap percentage was different for each external configuration (original wing or high AR wing) and for each composite PBM (ATL or AFP). Table 4.6 presents the 4 different values of technical scrap in this step of the process.

| Table 4.6: Technical Scrap in the Fibre Placement Stage for both PBM |
|---------------------------------|------------------|------------------|
| techn. scrap in Fibre Placement % | Original Wing | High AR wing |
| ATL | 60 | 69 |
| AFP | 54 | 56 |

The aluminium PBM had different part and material flows from the composite PBM presented previously. The information regarding the scrap material for each block was provided by the EMBRAER
company. In figure 4.10 is shown the number of part's material required in each step in order to obtain the final quantity for the expected of 100 parts per year. In stage number 7, the final inspection, there was not a large quantity of rejections since the whole process included visual inspection in order to detect the defected parts at the beginning of their production. In this way, the first steps of production needed to have scrap treatment in order to detect the errors as soon as possible in the production line to decrease the total cost of a single part. Stage number 2, the machining one, was the step in which more rejections.

Also in figure 4.10, is shown the material flow along the whole process for one aluminium part in order to obtain the projected part weight at the end of stage 7, final inspection. The technical scrap for the machining step was around 50%, so this macro block had the larger percentage of material wastage in all the process. Since each concept had different mass values, the initial material block that enters stage 1, material reception, had a different mass value for each configuration. Figure 4.10 shows those different values.

Having both diagrams shown in figure 4.10, it was possible to determine the material consumption
per year. For the different 4 aluminium wing configurations, in order to produce 100 parts it was required to have a very high quantity of material in which 63.3% of it will be scrap. The totals of material and parts for the aluminium model are shown in figure 4.11.

In table 4.7 is presented the global energy consumption of each distinct wing configuration. Although for the financial model the cost impact was very different for the two composite models, as it will be possible to check further on, in the environmental model the AFP model had very similar values when compared with the ATL model. Therefore, in the LCC the 2 production methods for composites were taken into account and for the LCA, only the ATL model was analysed and compared with the aluminium model.

Related to the energy consumption is the cycle time of each PBM. Regarding the aluminium model, the time in each process is presented in table 4.8.

Tables 4.9 and 4.10 present the total cycle time for the 2 production methods used to manufacture the same wing models but in composites.

With the resources consumption for each wing configuration and the cycle time in each stage of the models, the inventory of the PBM was defined. Therefore, the inputs related to the cost models were established and the financial model of the production phase was implemented.

The inventory for both financial and environmental models was the same in the production phase.
Table 4.7: Total Energy Consumption on the Production Phase for the different pair of Wing Configurations

<table>
<thead>
<tr>
<th>Concept</th>
<th>PBM</th>
<th>Energy Consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>10,666.23</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>43,594.17</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>30,690.31</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>10,946.60</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>47,007.96</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>32,895.58</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>10,663.82</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>53,688.31</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>31,670.18</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>10,763.08</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>55,256.04</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>32,490.39</td>
</tr>
</tbody>
</table>

Table 4.8: Cycle Time for the production in aluminium of each wing configuration, in hours

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no ribs</th>
<th>Wing 1, ribs</th>
<th>Wing 2, no ribs</th>
<th>Wing 2, ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Drilling</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JIG, Machining &amp; Part Adjustment</td>
<td>13.95</td>
<td>14.35</td>
<td>13.95</td>
<td>14.09</td>
</tr>
<tr>
<td>Inspection &amp; Penetrating Liquids</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape Testing &amp; Peening</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Treatment &amp; Painting</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge Trimming &amp; Processing</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Inspection</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>43.95</td>
<td>44.35</td>
<td>43.95</td>
<td>44.09</td>
</tr>
</tbody>
</table>

Table 4.9: Cycle Time for the production in composite of each wing configuration, by ATL model, in hours

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no ribs</th>
<th>Wing 1, ribs</th>
<th>Wing 2, no ribs</th>
<th>Wing 2, ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reception Check &amp; Storage</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application of copper &amp; GF layers</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>71.8</td>
<td>78.6</td>
<td>92</td>
<td>95.1</td>
</tr>
<tr>
<td>Application of GF layers</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autoclave</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demoulding Finishing &amp; Adjusting</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDT</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>112.8</td>
<td>119.6</td>
<td>133.0</td>
<td>136.1</td>
</tr>
</tbody>
</table>

Use - Inventory

With the total production costs determined, the next step was to calculate the cost of their useful life. Having the $\frac{t}{L}$ factor for the 2 different external configurations shown in table 4.2 in the aerodynamic analysis and the Breguet’s Equation, in expression 3.17, it was possible to obtain the fuel weight at the end of the cruise level and, according to the assumptions made, at the end of each flight. Breguet’s Equation gave the fuel weight ratios between the end and the beginning of the cruise mode (system 4.6).
Table 4.10: Cycle Time for the production in composite of each wing configuration, by AFP model, in hours

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no ribs</th>
<th>Wing 1, ribs</th>
<th>Wing 2, no ribs</th>
<th>Wing 2, ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reception Check &amp; Storage</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Application of copper &amp; GF layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>46</td>
<td>50.4</td>
<td>48</td>
<td>49.6</td>
</tr>
<tr>
<td>Application of GF layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autoclave</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demoulding Finishing &amp; Adjusting</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDT</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>87.0</td>
<td>91.4</td>
<td>89.0</td>
<td>90.6</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\left( \frac{W_f}{W_i} \right)_{original} &= 0.929314 \\
\left( \frac{W_f}{W_i} \right)_{HighAR} &= 0.939602
\end{align*}
\]

(4.6)

Knowing that at the beginning of the flight this aircraft had, for any wing configuration, a fuel weight of \( W_{fuel} = 14000 \) kg, at the end of the flight, for each external configuration, the fuel weight is shown in 4.7.

\[
\begin{align*}
W_{fuel_{original}} &= 13010.4 \text{ kg} \\
W_{fuel_{HighAR}} &= 13154.4 \text{ kg}
\end{align*}
\]

(4.7)

With the data of the fuel at the beginning and at the end of the flight for each configuration, it was possible to determine the value of the fuel consumption on a single flight in 4.8.

\[
\begin{align*}
\text{FC}_{original} &= 989.6 \text{ kg} \\
\text{FC}_{HighAR} &= 845.6 \text{ kg}
\end{align*}
\]

(4.8)

As it was predicted, the high \( AR \) configurations have a lower fuel consumption, so the costs regarding the use of the aircraft in which they are integrated were lower. For a fuel density of \( \rho_{fuel} = 0.72 \text{ kg/L} \), the volume of fuel consumed in a single flight was determined (system 4.9).

\[
\begin{align*}
V_{FC_{original}} &= 1374.4 \text{ L} \\
V_{FC_{HighAR}} &= 1174.4 \text{ L}
\end{align*}
\]

(4.9)

Since the total distance travelled in the aircraft’s useful life was assumed to be \( 105 \cdot 10^6 \text{ km} \), the total volume of fuel consumed during the aircraft’s life was determined in system 4.10.

\[
\begin{align*}
V_{FC_{original_{TOTAL}}} &= 3.896 \cdot 10^7 \text{ L} \\
V_{FC_{HighAR_{TOTAL}}} &= 3.329 \cdot 10^7 \text{ L}
\end{align*}
\]

(4.10)
**EOL - Inventory**

The boundaries for both financial and environmental models were the same and, in the *EOL* phase, the variables that were taken into account were the energy consumption and the material final disposal in the aircraft’s graveyards. The part’s *EOL* had distinct destinies according to the material from which they were built. In this thesis, as it was expressed in subsection 3.4.3, aluminium configurations were assumed to suffer a recycling process and the composite ones an incineration, in their respective *EOL* phases.

The cost of recycling an aluminium part was assumed to be at about 30% of its production cost [58], as it was exposed in subsection 3.4.3. On the other hand, the composite wings *EOL* costs due to incineration were considered null [59], as it was explained in subsection 3.4.3.

For the environmental impact, the material disposal for the aluminium wings was considered null due to recycling. However, it had a huge impact on the composite wings due to the incineration process.

**4.3.2 Cost Model - LCC**

**Production Phase**

Although the different *PBM* have different material flows, there were some inputs that they have in common. That data was provided by the Brazilian company *EMBRAER* for their *NOVEMOR* project. Those inputs are shown in table B.1, in annexe B.0.1.

In the composites’ production methods, material and scrap quantities were particular inputs that must be clarified and strictly determined in order to calculate the effective production volume per year and the initial material required to get the final configurations’ designs. The composite models needed an extra input which was the production efficiency. Either in the *ATL* or in the *AFP* models, the efficiency was assumed as 100% because the 4 different configurations require a complex production. In composite materials, the crucial parameters belonged to the carbon fibres. The composite material used for the analysis is characterized in subsection 3.1.2 of this thesis in terms of mechanical properties. The costs, number of layers, areal weight and layer height and carbon fibre inputs are shown in table B.2, in annexe B.0.1.

These models required also some characteristic inputs that assumed different values for each *PBM*. Regarding stage 5, autoclave, table B.3 in annexe B.0.1, shows its inputs as well as for the *ATL* and the *AFP* machines.

From table B.3 it is possible to check that the main difference from the *ATL* and the *AFP* machines was on their cycle time. This input was directly related to the theoretical formulas used to determine the lay-up rate expressed in system 3.24. The *AFP* machine had higher productivity than the machine used for *ATL* so the cycle time was lower in that *AFP* model’s stage. In a similar way to the metal’s model, the composite’s mould information is shown in table B.4, in annexe B.0.1.

Regarding the metal’s process, the variable costs such as the ones related to the material are given in table B.5, in annexe B.0.1. Although there were certain general inputs for the different models, shown in table B.1, table B.6 in annexe B.0.1 shows the inputs for the specific macro blocks of stages 2 (Machining)
and 3 (Penetrating liquids) for the aluminium model. It is also important, for the aluminium model, to specify the $JIC$ and the inspection time. In table B.7 in annexe B.0.1, are defined their particular inputs. The inputs shown in tables B.6 and B.7 were provided by the Brazilian Aircraft Company *EMBRAER*.

Before performing the analysis of the final results of the production phase in the *LCC*, intermediate calculations were important to be made. The scope followed for the *LCC*’s production phase is presented in figure 4.12.

![Figure 4.12: LCC’s production phase scope](image)

As figure 4.12 suggests, the first type of costs that were analysed were the variable costs. The 4 different aluminium wings had the same type of variable costs. The 4 composite wings also have the same variable costs distribution between them and there is no difference when they are manufactured by *ATL* or *AFP* processes. Table 4.11 shows the variable costs distribution for the two distinct material wings.

<table>
<thead>
<tr>
<th>Different Material Wings</th>
<th>Material</th>
<th>Energy</th>
<th>Labour</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>92%</td>
<td>3%</td>
<td>1%</td>
<td>4% (consumables)</td>
</tr>
<tr>
<td>Composite</td>
<td>98%</td>
<td>1%</td>
<td>0%</td>
<td>1% (scrap)</td>
</tr>
</tbody>
</table>

Although the material cost had a higher percentage for the composite wings, since it is a material more expensive than the aluminium, for both production methods the material cost corresponded to almost 100% of the variable costs.

With the variable costs analysed, it is important to check the fixed costs for the different production methods. In a similar way as in the variable costs, the 4 different aluminium wings, had the same distribution of their production fixed costs, which is presented in table 4.12. Also, for the composite models, the fixed costs had the same distribution for the different wing configurations even when they are produced by distinct models (*ATL* or *AFP*). Table 4.12 shows that distribution.

As it is possible to check from table 4.12, the machine’s cost for the composite models was almost $\frac{2}{3}$ of the total fixed costs. This happened due to the more complex processes that were required to manufacture composite structures.

In order to have a better comprehension of all the process stages, a cost analysis stage by stage
was performed. The material cost had a very significant impact as it is possible to check. This analysis is different for the 12 distinct wings. Tables 4.13, 4.14 and 4.15 show the cost per process phase.

Table 4.12: Fixed Costs Distribution for each different material wings

<table>
<thead>
<tr>
<th>Different Material Wings</th>
<th>Maintenance</th>
<th>Building</th>
<th>Fixed Overhead</th>
<th>Tooling</th>
<th>Main Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>6%</td>
<td>4%</td>
<td>29%</td>
<td>7%</td>
<td>54%</td>
</tr>
<tr>
<td>Composite</td>
<td>7%</td>
<td>2%</td>
<td>29%</td>
<td>0%</td>
<td>62%</td>
</tr>
</tbody>
</table>

The first line of tables 4.13, 4.14 and 4.15 represents the material cost. As it is possible to check, the material cost was the most significant one for all the 12 wing configurations. Therefore, an intermediate cost analysis of the different processes with and without material was performed, as tables 4.16, 4.17 and 4.18 show.

In the aluminium wings, the most expensive stage was the JIG placement & Machining. For the
Table 4.16: Analysis with and without material in aluminium wings, in euros

<table>
<thead>
<tr>
<th>Aluminium Process Stages</th>
<th>Material</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Drilling</td>
<td>yes</td>
<td>159</td>
<td>168</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JIG Placement &amp; Machining</td>
<td>yes</td>
<td>39,278</td>
<td>43,364</td>
<td>39,251</td>
<td>40,693</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>9,085</td>
<td>9,173</td>
<td>9,082</td>
<td>9,117</td>
</tr>
<tr>
<td>Penetration Liquids</td>
<td>yes</td>
<td>3,383</td>
<td>3,389</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape Testing &amp; Peening</td>
<td>yes</td>
<td>262</td>
<td>269</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Treatment &amp; Painting</td>
<td>yes</td>
<td>3,346</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>3,339</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge Trimming &amp; Processing</td>
<td>yes</td>
<td>55</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Inspection</td>
<td>yes</td>
<td>6</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.17: Analysis with and without material in composite wings manufactured through ATL model, in euros

<table>
<thead>
<tr>
<th>ATL Process Stages</th>
<th>Material</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Storage</td>
<td>yes</td>
<td>276</td>
<td>276</td>
<td>213</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>276</td>
<td>276</td>
<td>213</td>
<td>213</td>
</tr>
<tr>
<td>Copper &amp; GF layers</td>
<td>yes</td>
<td>4,036</td>
<td>4,512</td>
<td>4,031</td>
<td>4,200</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>116</td>
<td>120</td>
<td>115</td>
<td>117</td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>yes</td>
<td>328,739</td>
<td>368,153</td>
<td>422,715</td>
<td>440,701</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>8,134</td>
<td>8,945</td>
<td>8,611</td>
<td>9,959</td>
</tr>
<tr>
<td>GF layers Application</td>
<td>yes</td>
<td>677</td>
<td>753</td>
<td>676</td>
<td>703</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>54</td>
<td>55</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>Autoclave</td>
<td>yes</td>
<td>3,455</td>
<td>3,475</td>
<td>3,502</td>
<td>3,511</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>3,455</td>
<td>3,475</td>
<td>3,502</td>
<td>3,511</td>
</tr>
<tr>
<td>Demolding Finish. &amp; Adjusting</td>
<td>yes</td>
<td>2,891</td>
<td>2,949</td>
<td>3,030</td>
<td>3,056</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>2,891</td>
<td>2,949</td>
<td>3,030</td>
<td>3,056</td>
</tr>
<tr>
<td>Non-Destructive Tests</td>
<td>yes</td>
<td>1,382</td>
<td>1,416</td>
<td>1,451</td>
<td>1,466</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>1,332</td>
<td>1,361</td>
<td>1,401</td>
<td>1,414</td>
</tr>
</tbody>
</table>

Table 4.18: Analysis with and without material in composite wings manufactured through AFP model, in euros

<table>
<thead>
<tr>
<th>AFP Process Stages</th>
<th>Material</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Storage</td>
<td>yes</td>
<td>317</td>
<td>317</td>
<td>303</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>317</td>
<td>317</td>
<td>303</td>
<td>303</td>
</tr>
<tr>
<td>Copper &amp; GF layers</td>
<td>yes</td>
<td>4,037</td>
<td>4,512</td>
<td>4,032</td>
<td>4,201</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>117</td>
<td>121</td>
<td>117</td>
<td>118</td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>yes</td>
<td>284,336</td>
<td>318,429</td>
<td>296,843</td>
<td>309,463</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>5,479</td>
<td>5,996</td>
<td>5,637</td>
<td>5,828</td>
</tr>
<tr>
<td>GF layers Application</td>
<td>yes</td>
<td>646</td>
<td>718</td>
<td>645</td>
<td>671</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>54</td>
<td>55</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>Autoclave</td>
<td>yes</td>
<td>3,393</td>
<td>3,405</td>
<td>3,397</td>
<td>3,402</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>3,393</td>
<td>3,405</td>
<td>3,397</td>
<td>3,402</td>
</tr>
<tr>
<td>Demolding Finish. &amp; Adjusting</td>
<td>yes</td>
<td>2,703</td>
<td>2,738</td>
<td>2,716</td>
<td>2,729</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>2,703</td>
<td>2,738</td>
<td>2,716</td>
<td>2,729</td>
</tr>
<tr>
<td>Non-Destructive Tests</td>
<td>yes</td>
<td>1,288</td>
<td>1,311</td>
<td>1,294</td>
<td>1,303</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>1,238</td>
<td>1,256</td>
<td>1,244</td>
<td>1,251</td>
</tr>
</tbody>
</table>
composite wings, in both models, the most expensive stage was the *Fibre Placement*, since it was when the most significant part of material was used. Including the time variable in the costs per stage, the costs per process hour were determined and are presented in tables 4.19, 4.20 and 4.21.

Table 4.19: Cost per process hour in aluminium wings, in *euros*

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Drilling</td>
<td>56</td>
<td>436</td>
<td>436</td>
<td>434</td>
</tr>
<tr>
<td>JIG Placement &amp; Machining</td>
<td>436</td>
<td>430</td>
<td>436</td>
<td>434</td>
</tr>
<tr>
<td>Penetration Liquids</td>
<td>484</td>
<td>484</td>
<td>484</td>
<td>484</td>
</tr>
<tr>
<td>Shape Testing &amp; Peening</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Surface Treatment &amp; Painting</td>
<td>334</td>
<td>334</td>
<td>334</td>
<td>334</td>
</tr>
<tr>
<td>Edge Trimming &amp; Processing</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Final Inspection</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4.20: Cost per process hour in composite wings manufactured through *ATL* model, in *euros*

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Storage</td>
<td>69</td>
<td>69</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Copper and GF layers Application</td>
<td>19</td>
<td>20</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>113</td>
<td>114</td>
<td>104</td>
<td>105</td>
</tr>
<tr>
<td>GF layers Application</td>
<td></td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Autoclave</td>
<td>247</td>
<td>248</td>
<td>250</td>
<td>251</td>
</tr>
<tr>
<td>Demolding Finishing &amp; Adjusting</td>
<td>578</td>
<td>590</td>
<td>606</td>
<td>611</td>
</tr>
<tr>
<td>Non-Destructive Tests</td>
<td>222</td>
<td>227</td>
<td>234</td>
<td>236</td>
</tr>
</tbody>
</table>

Table 4.21: Cost per process hour in composite wings manufactured through *AFP* model, in *euros*

<table>
<thead>
<tr>
<th>Stages</th>
<th>Wing 1, no Ribs</th>
<th>Wing 1, Ribs</th>
<th>Wing 2, no Ribs</th>
<th>Wing 2, Ribs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Reception &amp; Storage</td>
<td>79</td>
<td>79</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>Copper and GF layers Application</td>
<td>673</td>
<td>752</td>
<td>672</td>
<td>700</td>
</tr>
<tr>
<td>Fibre Placement</td>
<td>6,182</td>
<td>6,318</td>
<td>6,190</td>
<td>6,240</td>
</tr>
<tr>
<td>GF layers Application</td>
<td></td>
<td></td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>Autoclave</td>
<td>242</td>
<td>243</td>
<td>243</td>
<td>243</td>
</tr>
<tr>
<td>Demolding Finishing &amp; Adjusting</td>
<td>540</td>
<td>548</td>
<td>543</td>
<td>546</td>
</tr>
<tr>
<td>Non-Destructive Tests</td>
<td>214</td>
<td>219</td>
<td>216</td>
<td>217</td>
</tr>
</tbody>
</table>

With the intermediate production costs determined it was possible to calculate the total costs distribution, represented in figures 4.22, 4.23 and 4.24.

The final value of manufacturing 2 wings of each of the 4 different configurations by each one of the *PBCM*’s is presented in table 4.25.

From table 4.25 it is possible to understand that the metal’s manufacturing processes are much cheaper than the composite ones. The composite processes are approximately 8 times more expensive. However, making a distinction in the composites’ models, the *AFP* is significantly less expensive than the *ATL* process. Making a global comparison between the wings, the introduction of ribs increases the production cost, since the quantity of material required is larger. In the composites manufacturing processes, wings with a higher aspect ratio are more expensive. This phenomena does not occur for metal’s production models as it is possible to check from table 4.25. In this way, the wing configuration
with the cheapest manufacturing process, out of the 12 analysed, was the high aspect ratio wing without ribs, produced in aluminium. However, the cost difference between this wing and the original external configuration without ribs produced in the same material was insignificant.

From tables 4.20 and 4.21 it is possible to conclude that the cost per process hour in the ATL model was cheaper than in the AFP model. However, table 4.6 gives the information that the material waste was much more in the ATL model. In this way, even with a more expensive stage of fibre placement, the AFP model produced cheaper wings due to the lower material waste in the whole manufacturing process.

With the production costs determined it was necessary to calculate the use costs for a pair of wing’s total life, in order to project the investment needed for the different configurations studied.
<table>
<thead>
<tr>
<th>Concept</th>
<th>PBCM</th>
<th>Production Costs (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>46,489</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>341,455</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>296,769</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>50,575</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>381,534</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>331,430</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>46,462</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>453,850</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>309,231</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>47,904</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>453,850</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>322,072</td>
</tr>
</tbody>
</table>

Use Costs

The boundaries for both financial and environmental models were the same and, in the use phase, the variable that was taken into account was the blocks of fuel consumed during the aircraft’s useful life.

With the total volume of fuel consumed by the different pair of wings in their aircraft’s useful life, expressed in system 4.10, the price per litre of fuel was needed in order to determine the total use costs.

For a fuel price per litre of $Cost_{fuel} = 1.51$ euros/L, the total cost of the different wing configurations’ use is presented in table 4.26.

<table>
<thead>
<tr>
<th>Original Wing</th>
<th>High $AR$ Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.83</td>
<td>50.30</td>
</tr>
</tbody>
</table>

From table 4.26 it is possible to check that the wings with a higher aspect ratio induce an aircraft to have lower values of blocks of fuel consumed during its useful life, due to a higher $l/D$ ratio. Therefore, this wing configuration will be less expensive and also less pollutant than the original external configuration wings provided by EMBRAER in project NOVEMOR. The $LCC$ of the different concepts was only determined when the 3 types of costs are established. The next step was to determine the $EOL$ costs.

$EOL$ Costs

Taking into account the methodology followed in subsection 3.4.3 in which it was assumed that the cost of recycling an aluminium part was 30% of its production cost [58] and for the composite wings, the $EOL$ costs due to incineration were considered null [59], table 4.27 gives de $EOL$ costs for each wing configuration.
Table 4.27: EOL Costs of the different pair of Wing Configurations

<table>
<thead>
<tr>
<th>Concept</th>
<th>PBCM</th>
<th>EOL Costs (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>13,947</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>15,173</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>13,939</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>14,371</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0</td>
</tr>
</tbody>
</table>

Life Cycle Costs

With the values for the calculations of the EOL costs for each wing, it was needed to clarify the total costs in terms of production, use and EOL. Table 4.28 exposes the final LCC results, for the financial model.

Table 4.28: Total Costs of the different Wing Configurations

<table>
<thead>
<tr>
<th>Concept</th>
<th>PBCM</th>
<th>Production Cost (euro)</th>
<th>Use Cost (euro)</th>
<th>EOL Cost (euro)</th>
<th>Total Cost (euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>46,489</td>
<td>58,831,300</td>
<td>13,947</td>
<td>58,891,736</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>341,455</td>
<td>58,831,300</td>
<td>0</td>
<td>59,172,755</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>296,769</td>
<td>58,831,300</td>
<td>0</td>
<td>59,128,069</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>50,575</td>
<td>58,831,300</td>
<td>15,173</td>
<td>58,897,048</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>381,534</td>
<td>58,831,300</td>
<td>0</td>
<td>59,212,834</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>331,430</td>
<td>58,831,300</td>
<td>0</td>
<td>59,162,730</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>46,462</td>
<td>50,270,300</td>
<td>13,939</td>
<td>50,330,701</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>435,617</td>
<td>50,270,300</td>
<td>0</td>
<td>50,705,917</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>309,231</td>
<td>50,270,300</td>
<td>0</td>
<td>50,579,531</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>47,904</td>
<td>50,270,300</td>
<td>14,371</td>
<td>50,332,575</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>453,850</td>
<td>50,270,300</td>
<td>0</td>
<td>50,724,150</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>332,072</td>
<td>50,270,300</td>
<td>0</td>
<td>50,592,372</td>
</tr>
</tbody>
</table>

From table 4.28 it is possible to check that the life cycle phase that had more impact in the wing configurations’ cost was the use phase. Therefore, wings with a higher aspect ratio would have a relevant advantage when compared to the other wings. After the use phase, the production is the stage that has more impact in the wings’ LCC. Therefore, a wing produced in aluminium would have an advantage when compared to a composite wing. Also, the quantity of material used had also impact on the production phase costs. Therefore, from table 4.28, the wing with the cheapest life cycle cost was the high aspect ratio wing, without ribs produced in aluminium. On the other hand, the most expensive wing from out the 12 different configurations was the original wing, with ribs, made in composite by ATL process.

With the LCC analysis totally performed and with its results obtained, it was necessary to check the
4.3.3 Environmental Model - LCA

Production Environmental Impact

For the same resources consumption considered as in the financial model, the environmental model for the production phase gave an endpoint analysis, represented in table 4.29. It was developed a model in SimaPro and the Sankey graphics are exposed in annex C. From the endpoint analysis of the production phase it is possible to conclude that the introduction of ribs increased the environmental impact since the quantity of material used was higher. Also, composite wings had a much more pollutant production phase than aluminium wings.

Use Environmental Impact

In the use phase the variable taken into account was only the blocks of fuel consumed during the entire aircraft’s useful life. Therefore, the wing’s material was not considered as a variable in this phase and, consequently, the endpoint analysis gave the same results for certain aluminium or composite wing. Table 4.29 shows the environmental impact of each wing configuration.

The input $\frac{L}{D}$ ratio given by the aerodynamic analysis held the main differences between the concepts in their use phase either for the financial model or for the environmental model. Therefore, it was assumed that the internal configuration (having or not having ribs) did not change the environmental impact of the wings in this phase. It is possible to conclude that the external wing configuration had a really significant impact on the environment during an aircraft’s useful life. The wings with a higher aspect ratio had higher $\frac{L}{D}$ values and, by the Breguet's Equation 3.17, consumed less fuel in their flights. This fuel consumption impact is expressed in table 4.29.

EOL Environmental Impact

In the EOL phase, the resources considered were the material and the energy. Different material parts expect distinct EOL scenarios. It was considered that the metal components were recycled and the composite parts were incinerated. Therefore, the energy consumed in those processes and the material final disposal were taken into account. In table 4.29 are shown the impacts of these two different final disposal options.

Life Cycle Assessment

Table 4.29 shows the different environmental impacts that the same wing configurations had when they were manufactured in metal or in composite. As it was expected, the composite wings had much more environmental negative consequences in their EOL phase than the aluminium wings. The introduction of ribs induced an increment on the part’s environmental impact since the quantity of material was higher.
Table 4.29: Environmental Impacts in each life cycle phase for the 4 distinct wing configurations built in aluminium and composite, in kilopoints

<table>
<thead>
<tr>
<th>Concept</th>
<th>Material</th>
<th>Production</th>
<th>Use</th>
<th>EOL</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>3.4</td>
<td>115.0</td>
<td>0.4</td>
<td>118.8</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>4.65</td>
<td>115.0</td>
<td>1.2</td>
<td>120.05</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>3.7</td>
<td>115.0</td>
<td>0.4</td>
<td>119.1</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>4.9</td>
<td>115.0</td>
<td>2.0</td>
<td>121.9</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>3.4</td>
<td>72.5</td>
<td>0.4</td>
<td>76.3</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>4.5</td>
<td>72.5</td>
<td>1.2</td>
<td>78.2</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>3.7</td>
<td>72.5</td>
<td>0.4</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>4.75</td>
<td>72.5</td>
<td>2.0</td>
<td>79.25</td>
</tr>
</tbody>
</table>

The different wings’ net resources have some differences specially in the EOL solution, as figures C.1 to C.8 in appendix C show.

In these net resources it is represented the impact of the 3 stages of a pair of wing’s life cycle, including its production, its use and its EOL. Therefore, the impact is related to the total weight of 2 wings in the production that will also affect its useful life and finally its EOL.

In order to perform a clear and direct comparison in environmental terms an Analytical Hierarchy Process was performed. The global environmental impact of the 3 life cycle phases of all the wings was classified from 0 (worst) to 12 (best) in order to get a final classification in which the one with the highest score is the best wing, in environmental terms. In table 4.30, this environmental evaluation was performed and the wing with lower environmental impact was obtained.

Table 4.30: Environmental Comparison between the distinct 4 wing configurations built in aluminium and composite

<table>
<thead>
<tr>
<th>Concept</th>
<th>Material</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>0.49</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>0.00</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>12.00</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>11.50</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>11.92</td>
</tr>
<tr>
<td></td>
<td>Composite</td>
<td>11.22</td>
</tr>
</tbody>
</table>

From the results of table 4.30 it is possible to conclude that the high aspect ratio wing configuration without ribs, manufactured in aluminium, was the one with lower environmental impact.

### 4.4 Parametric Studies: COMSOL

It was assumed that the different materials used in the wing’s production did not affect their aerodynamic behaviour. Thus, it was performed a parametric study regarding mixtures with distinct quantities of aluminium and composite and their structural behaviour. Also, from that parametric study, it was possible
to analyse the cost and environmental impact variations, in a qualitative way, and check how some intermediate stages between 100% aluminium and 100% composite would be relevant alternatives in this industry. The analysis was performed in the software COMSOL MultiPhysics provided by T. U. Delft. The wings tested were very complex structures and behaved as cantilevered beams, with a distributed pressure on their lower surface with positive Oz direction, as it was possible to understand from some of the vibration and buckling modes from the structural analysis in subsection 4.2. Figure D.1 in annexe D shows this 2 layered beam in which the variables of this analysis were only the thickness of the 2 plies and its mesh. However, the sum of the 2 thickness values was kept constant.

The beam’s dimensions assumed were a total thickness of 0.05 m, a width of 0.25 m and a length of 2 m. A pressure of 1 N/m² was applied in the lower surface with positive direction Oz and one of the smallest surfaces was cantilevered. As it was already established, the plies’ thickness assumed different percentages of the total value and the top layer was made in composite and the lower layer in aluminium, in order to get a clearer comparison.

In the structural domain, the results taken into account for this parametric study were the ones obtained from the static analysis, regarding the maximum tip displacement and the von-Mises stress. Table 4.31 presents the static analysis of this simple cantilevered beam with a distributed load along its lower surface.

<table>
<thead>
<tr>
<th>Beam Structure Composition</th>
<th>von-Mises stress [KPa]</th>
<th>maximum tip displacement [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{al} = t_{total}$</td>
<td>4</td>
<td>$2.5 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{comp} = t_{total}$</td>
<td>4</td>
<td>$1.0 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{al} = \frac{1}{2} \cdot t_{total}$ &amp; $t_{comp} = \frac{1}{2} \cdot t_{total}$</td>
<td>6</td>
<td>$1.6 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{al} = \frac{3}{4} \cdot t_{total}$ &amp; $t_{comp} = \frac{1}{4} \cdot t_{total}$</td>
<td>6</td>
<td>$1.8 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{al} = \frac{1}{2} \cdot t_{total}$ &amp; $t_{comp} = \frac{3}{2} \cdot t_{total}$</td>
<td>5</td>
<td>$1.4 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{al} = \frac{3}{5} \cdot t_{total}$ &amp; $t_{comp} = \frac{2}{5} \cdot t_{total}$</td>
<td>5</td>
<td>$1.7 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t_{al} = \frac{1}{3} \cdot t_{total}$ &amp; $t_{comp} = \frac{2}{3} \cdot t_{total}$</td>
<td>5</td>
<td>$1.5 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

Since the load applied is very low, the von-Mises stress had an unconventional variation and, as a consequence, its results were inconclusive. However, the values of the maximum tip displacement followed a pattern and were possible to analyse and to take some conclusions from them. Therefore, the parametric study was focused on the displacement and the plies’ thickness.

In figure 4.13 is possible to check the bending movement produced in the cantilevered beam by the constant distributed load.

The maximum displacement for the other beam configurations is presented in annexe D.

In order to have the lowest tip displacement balanced with the lowest production cost, this simple model can represent a fast way to get this correlation. For that, different functions were created based on equation 4.11.

$$f(x) = w_1 \cdot f_1(x) + w_2 \cdot f_2(x),$$

(4.11)

in which $f(x)$ was the objective function, $f_1(x) = \frac{\text{vector\_cost}}{\text{cost\_max}}$, $f_2(x) = \frac{\text{vector\_displacement}}{\text{displacement\_max}}$, $w_1$ was the vector
with the different weights applied to the cost dimensionless function and \( w_2 \) was the vector with the different weights applied to the displacement dimensionless function.

\( w_1 \) and \( w_2 \) gave different weights to each dimensionless function and the length of this vectors was 5. The 5 different functions were generated, as figure 4.14 exposes.

As it is possible to check from figure 4.14, the different functions intersect all in the same point. The \( x \) coordinate of that point gives a composite thickness of 16.822 mm and an aluminium thickness of 33.178 mm, which corresponds, respectively, to 33.64% of composite and 66.36% of aluminium.

The main objective of this parametric study was to achieve the best correlation between the Structural Analysis and the Production Cost Analysis for a simplified body that has a similar behaviour as the wings tested.

Some wing’s configurations have better performance in the structural behaviour, others are cheaper, some of them have better aerodynamic results and other wings have a really large environmental impact. In this parametric study, aerodynamic results were not taken into account because the external shape of the body analysed is the same. Therefore, the best balance to perform is between the costs and the structural behaviour.

With this extra analysis performed besides the other ones, conclusions may be taken and solutions may be created in order to get the most suitable configuration for each aircraft company.
Chapter 5

Conclusions

5.1 Achievements & Key Takeaways

With the 3 different analyses the main goal of this thesis was achieved using an Analytical Hierarchy Process (AHP). It was considered that the aerodynamic behaviour, the structural response and the economic and environmental evaluations had the same importance in the classification of the different 12 wing configurations. Therefore, the weight of each of these 4 categories was considered to be 25% of the total evaluation. The wings were evaluated from 0 (worst) to 12 (best) in each of those 4 categories.

For the aerodynamic category, the most influential result was the $L/D$ ratio. Nevertheless, the coefficient of moment $C_M$ was also taken into account to perform the aerodynamic evaluation. Since these variables only had different results for changes in the external dimension, there are only 2 different results in this analysis. The material and the internal configuration did not affect the aerodynamic results. Therefore, the original external wing configurations had lower aerodynamic classification (1 out of 12) than the high aspect ratio wings (12 out of 12), since their flight performance is worse. Regarding the structural behaviour, the principal focus of this evaluation was based on the static analysis (both maximum stress and maximum tip displacement). However, the vibration and buckling modes also contributed for the structural evaluation of the different wings. The configurations considered with better structural behaviour were the ones with lower values of maximum tip displacement and maximum stress.

In the structural analysis, both wings manufactured by ATL and AFP processes had the same behaviour and, consequently, the same classification. As it was concluded in subsection 4.2.1, the composite used in the analyses was not the most suitable one for this type of simulations. In this way, the structural response of the composite wings was worse than the one from the metal wings. However, the introduction of ribs in any wing configuration increased its structural classification since these components increase the wings’ structural resistance. In a general way, the wings with higher aspect ratio had worse structural results since this wings were longer and narrower so, as it was expected, the maximum tip displacement was higher. For the LCC analysis, the 12 wings were classified from the cheapest to the most expensive, taking into account the expenses of the 3 phases of the wing’s life cycle. The fourth classification category is the wings’ LCA. All the 3 life cycle phases were considered as in the LCC evaluation. In this
category, composite wings have more environmental impact than the metal wings due to the fact that for their EOL phase was considered incineration and for the aluminium wings was assumed a recycling process. Also because in the production phase the energy required for composite production methods was higher than for the metal models. Regarding the use phase, low aspect ratio wings had worse aerodynamic performance and, consequently, the blocks of fuel consumed were larger. The introduction of ribs in order to raise the structural resistance also had a negative impact on the environment since more material was used on the production phase, inducing a growth on the energy consumption on this phase. Table 5.1 presents the AHP performed to evaluate the distinct wing configurations.

<table>
<thead>
<tr>
<th>Concept</th>
<th>PBCM</th>
<th>Aerodynamics (25%)</th>
<th>Structural (25%)</th>
<th>LCC (25%)</th>
<th>LCA (25%)</th>
<th>Total (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing 1, no ribs</td>
<td>Metal</td>
<td>0.00</td>
<td>11.99</td>
<td>0.43</td>
<td>0.82</td>
<td>3.31</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0.00</td>
<td>11.23</td>
<td>0.05</td>
<td>0.49</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0.00</td>
<td>11.23</td>
<td>0.11</td>
<td>0.49</td>
<td>2.96</td>
</tr>
<tr>
<td>Wing 1, ribs</td>
<td>Metal</td>
<td>0.00</td>
<td>12.00</td>
<td>0.43</td>
<td>0.74</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>0.00</td>
<td>11.25</td>
<td>0.00</td>
<td>0.00</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>0.00</td>
<td>11.25</td>
<td>0.07</td>
<td>0.00</td>
<td>2.83</td>
</tr>
<tr>
<td>Wing 2, no ribs</td>
<td>Metal</td>
<td>12.00</td>
<td>5.64</td>
<td>12.00</td>
<td>12.00</td>
<td>10.41</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>12.00</td>
<td>0.00</td>
<td>11.49</td>
<td>11.50</td>
<td>8.75</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>12.00</td>
<td>0.00</td>
<td>11.66</td>
<td>11.50</td>
<td>8.79</td>
</tr>
<tr>
<td>Wing 2, ribs</td>
<td>Metal</td>
<td>12.00</td>
<td>5.68</td>
<td>11.99</td>
<td>11.92</td>
<td>10.40</td>
</tr>
<tr>
<td></td>
<td>ATL</td>
<td>12.00</td>
<td>0.06</td>
<td>11.47</td>
<td>11.22</td>
<td>8.68</td>
</tr>
<tr>
<td></td>
<td>AFP</td>
<td>12.00</td>
<td>0.06</td>
<td>11.65</td>
<td>11.22</td>
<td>8.73</td>
</tr>
</tbody>
</table>

From table 5.1 the best wing out from out the 12 wing configurations was a high aspect ratio wing, without the introduction of ribs and manufactured in aluminium. This concept had the final highest score of 10.41 out of 12 possible. However, it is important to be clear that many assumptions had to be made during the analyses development that, without them, the results obtained could be very different. Specially, a change on the last assumption in which each of the 4 categories had a weight of 25% of the total evaluation could have many derivations and conduce to very different results. Besides these variations, there are several key takeaways that must be taken out from this work:

- The increase of a wing’s aspect ratio, for the same wing area, increases its $L/D$ factor;
- Wings with higher $L/D$ factor have better aerodynamic performance (since they allow to achieve the same lift with a smaller drag) and, consequently, consume smaller blocks of fuel during their useful life;
- Wings with higher aspect ratios have higher values of maximum tip displacement for the same load applied;
- The introduction of ribs in a wing’s internal configuration decreases its maximum tip displacement providing extra structural resistance to the body;
- Not every composite configuration is suitable to this specific simulation model. It was expected a
better structural response from the composite wings when compared to the aluminium ones and it did not happen due to the number of layers, fibre orientation and layers' thickness;

- For large bodies such as wings, the majority of their variable production costs (above 90% for metal and composite models) are material costs;

- In composites’ production methods, the material cost is even higher since composite raw material is more expensive than aluminium;

- Composites’ manufacturing processes are at about 8 times more expensive than metal processes, for this type of parts;

- Within the composites’ manufacturing processes, for the same wing configuration, ATL model is more expensive than AFP model, due to the material waste;

- Composite wings’ production has a higher environmental impact than aluminium wings since the energy used in their production phase is higher;

- The introduction of ribs in the wings internal structure also has a negative impact on the environment because the material quantity involved in the process is bigger;

- The actual scenarios for the composites’ final disposal are not suitable in terms of environmental concerns. Therefore the options for metal’s EOL, which include recycling material to other industries, are way ahead from composite’s EOL destinations.

The major goal of the present work was achieved since insights on the design of a wing configuration were provided, considering aerodynamics, structures, costs and environmental impact. The pros and cons of each configuration were taken into account and this multidisciplinary project was successfully enrolled and concluded.

## 5.2 Future Work

The major idea for future work, based on this thesis, could be the generation of an optimization model in order to achieve an optimal wing configuration. This process should start by the minimization of an objective function and the body to optimize would be the simplified model provided for this thesis by EMBRAER in project NOVEMOR. The design variables could be the skin and spars’ thickness. These variables would change not only the objective function, but also the structural constraints imposed. Von-Mises criteria could be the one to establish the structural constraints in the wing’s model. Figure 5.1 shows the objective function’s graphic.

The main goal would be to get the lighter and cheaper wing as possible without failing the structural constraints. This way, the analysis would be more precise than the one performed in this thesis since it would not be discrete. Once the objective function gave the optimal wing, it would be important to analyse its use and EOL phase, as it was performed in this thesis.
Another future work should be started based on this first one in which the use and EOL phases of the optimal wing configuration are analysed. A suggestion for that is to create a database with the energy required for each EOL option for each wing geometry dependent on its material. Another database could be created in order to determine the use phase in a more clear and refined way. Inputs such as cruise altitude, total fuel weight, aircraft's fuel consumption, fuel price, flight range and total distance fleet in the aircraft's useful life, would be the requirements to get the result of the aircraft's use cost. With this optimization model it would be possible to get not only an optimum wing for NOVEMOR project, but also its total analysis regarding its complete life cycle.

As it is possible to conclude from the results obtained for the EOL phase, the composite's incineration has a huge environmental impact when compared with the recycling process used for aluminium components. Therefore, new alternatives must be developed in order to achieve a less pollutant waste treatment and disposal methods option for the composite configurations in the aeronautical industry. As it happens for metals, in the aeronautical industry it is not possible to use recycled materials in the components manufactured. However, the older ones in their EOL phase can be recycled to other industries. This should be applied also to the composite parts in order to reduce the environmental impact of their last life cycle phase. The construction industry could be a suitable market to provide the consequent results of a composite's recycling or reuse process. However, the recycled composite materials would be subjected to the construction legislation in order to check if they fulfilled the requirements of that industry. Recycling composite to other industries should be studied. Other alternative to composite final disposal is landfill of industrial waste. The problem of this landfilling alternative is that the volume occupied by the component is much more than when its incinerated. The environmental impacts of landfill are also significant mainly, as said above, by the land occupation. On the other hand, incineration has a very high environmental risk due to the gas emissions, but the part is reduced to almost 1 or 2% of its initial volume. Regarding the incineration costs, since this process has a good energy efficiency, the costs are low when compared to the recycling process performed in metals. Since these issues should be analysed in a multidisciplinary way, other alternatives must be studied in the present in order to reduce future negative consequences on the environment.
Bibliography


Appendix A

Structural Analysis

Figure A.1: Maximum Tip Displacement for the 8 configurations

Figure A.2: Maximum Stress for the 8 configurations
Figure A.3: Modal Analysis for the original wing, without ribs, made in aluminium A6061

Figure A.4: Modal Analysis for the original wing, without ribs, made in composite
Figure A.5: Modal Analysis for the original wing, with ribs, made in aluminium A6061

Figure A.6: Modal Analysis for the original wing, with ribs, made in composite
Figure A.7: Modal Analysis for the high AR wing, without ribs, made in aluminium A6061

Figure A.8: Modal Analysis for the high AR wing, without ribs, made in composite
Figure A.9: Modal Analysis for the high AR wing, with ribs, made in aluminium A6061

Figure A.10: Modal Analysis for the high AR wing, with ribs, made in composite
Figure A.11: *Linear Buckling Analysis* for the original wing, without ribs, made in aluminium A6061

Figure A.12: *Linear Buckling Analysis* for the original wing, without ribs, made in composite
Figure A.13: *Linear Buckling Analysis* for the original wing, with ribs, made in aluminium *A6061*

Figure A.14: *Linear Buckling Analysis* for the original wing, with ribs, made in composite
Figure A.15: Linear Buckling Analysis for the high $AR$ wing, without ribs, made in aluminium $A6061$

Figure A.16: Linear Buckling Analysis for the high $AR$ wing, without ribs, made in composite
Figure A.17: Linear Buckling Analysis for the high AR wing, with ribs, made in aluminium A6061

Figure A.18: Linear Buckling Analysis for the high AR wing, with ribs, made in composite
# Appendix B

## LCC

### B.0.1 LCC - inputs

**Table B.1: General Inputs**

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
<th>Unities</th>
</tr>
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<tbody>
<tr>
<td>Days per Year</td>
<td>240</td>
<td>days/year</td>
</tr>
<tr>
<td>Total Wage of a worker</td>
<td>6</td>
<td>euro/h</td>
</tr>
<tr>
<td>Unit Energy Cost</td>
<td>0.08</td>
<td>euro/kWh</td>
</tr>
<tr>
<td>Opportunity Cost Rate</td>
<td>15</td>
<td>%</td>
</tr>
<tr>
<td>Equipment’s Life</td>
<td>15</td>
<td>years</td>
</tr>
<tr>
<td>Building Unit Cost</td>
<td>1,500</td>
<td>euro/m²</td>
</tr>
<tr>
<td>Building’s Life</td>
<td>30</td>
<td>years</td>
</tr>
<tr>
<td>Production’s Life</td>
<td>15</td>
<td>years</td>
</tr>
<tr>
<td>Idle Space</td>
<td>20</td>
<td>%</td>
</tr>
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</table>

**Table B.2: Carbon Fibre Inputs**

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
<th>Unities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap Price</td>
<td>5</td>
<td>euro/kg</td>
</tr>
<tr>
<td>Cost per sqm</td>
<td>30</td>
<td>euro/m²</td>
</tr>
<tr>
<td>Number of Layers</td>
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<td>-</td>
</tr>
<tr>
<td>Layer Thickness</td>
<td>0.135</td>
<td>mm</td>
</tr>
<tr>
<td>Areal Weight</td>
<td>300</td>
<td>g/m²</td>
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Table B.3: Inputs for ATL and AFP Machines and for Autoclave Stage in the Composite Models

<table>
<thead>
<tr>
<th>Input</th>
<th>ATL</th>
<th>AFP</th>
<th>Autoclave</th>
<th>Unities</th>
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<tr>
<td>Machine Dedicated</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Number of Workers</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Dedication</td>
<td>100</td>
<td>100</td>
<td>66</td>
<td>%</td>
</tr>
<tr>
<td>Area Required</td>
<td>30</td>
<td>30</td>
<td>60</td>
<td>m²</td>
</tr>
<tr>
<td>Number of Units</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>500</td>
<td>500</td>
<td>1200</td>
<td>kW</td>
</tr>
<tr>
<td>Acquisition Cost</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Million euros</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>6.55</td>
<td>5</td>
<td>14</td>
<td>h</td>
</tr>
<tr>
<td>Maintenance</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>%</td>
</tr>
<tr>
<td>Overheads</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>%</td>
</tr>
<tr>
<td>Allocation for Part</td>
<td>55</td>
<td>55</td>
<td>60</td>
<td>%</td>
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Table B.4: Mould and Consumables information for the Composite Models

<table>
<thead>
<tr>
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<th>value</th>
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</tr>
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<tbody>
<tr>
<td>Number of Moulds</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Mould's Cost</td>
<td>0.03</td>
<td>Million euros</td>
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<tr>
<td>Mould's Setup</td>
<td>5</td>
<td>h</td>
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<tr>
<td>Consumables</td>
<td>10</td>
<td>euro/m²</td>
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Table B.5: Aluminium Costs

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<th>value</th>
<th>Unities</th>
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</thead>
<tbody>
<tr>
<td>Aluminium Cost</td>
<td>10</td>
<td>euro/kg</td>
</tr>
<tr>
<td>Scrap Price</td>
<td>0.5</td>
<td>euro/kg</td>
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</table>

Table B.6: Inputs for Machining and Penetrating Liquids stages in the Aluminium Model

<table>
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<th>Machining</th>
<th>Penetrating Liquids</th>
<th>Unities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Dedicated</td>
<td>No</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Number of Workers</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Dedication</td>
<td>100</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Area Required</td>
<td>200</td>
<td>30</td>
<td>m²</td>
</tr>
<tr>
<td>Number of Units</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>700</td>
<td>100</td>
<td>kW</td>
</tr>
<tr>
<td>Acquisition Cost</td>
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<td>3</td>
<td>Million euros</td>
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<tr>
<td>Cycle Time</td>
<td>2.25</td>
<td>4</td>
<td>h</td>
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<td>Maintenance</td>
<td>10</td>
<td>10</td>
<td>%</td>
</tr>
<tr>
<td>Overheads</td>
<td>40</td>
<td>40</td>
<td>%</td>
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<tr>
<td>Allocation for Part</td>
<td>15</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td>Consumables</td>
<td>1</td>
<td>1</td>
<td>units/h</td>
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<td>Consumables Cost</td>
<td>150</td>
<td>42</td>
<td>euro/unit</td>
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Table B.7: JIG and Inspection information for the Aluminium Model

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<th>Unities</th>
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</thead>
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<tr>
<td>Number of JIGs</td>
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<td>JIG’s Cost</td>
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<td>Million euros</td>
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<td>JIG’s Setup</td>
<td>2</td>
<td>h</td>
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<tr>
<td>Inspection Time</td>
<td>4</td>
<td>h</td>
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Appendix C

LCA

(a) Total Net Resources of the original wing without ribs made in aluminium

Figure C.1: Net Resources for the original wing without ribs made in aluminium

(b) Production Net Resources of the original wing without ribs made in aluminium

(a) Total Net Resources of the original wing without ribs made in composite

Figure C.2: Net Resources for the original wing without ribs made in composite
(a) Total Net Resources of the original wing with ribs made in aluminium

(b) Production Net Resources of the original wing with ribs made in aluminium

Figure C.3: Net Resources for the original wing with ribs made in aluminium

(a) Total Net Resources of the original wing with ribs made in composite

(b) Production Net Resources of the original wing with ribs made in composite

Figure C.4: Net Resources for the original wing with ribs made in composite
(a) Total Net Resources of the high AR wing without ribs made in aluminium

(b) Production Net Resources of the high AR wing without ribs made in aluminium

Figure C.5: Net Resources for the high AR wing without ribs made in aluminium

(a) Total Net Resources of the high AR wing without ribs made in composite

(b) Production Net Resources of the high AR wing without ribs made in composite

Figure C.6: Net Resources for the high AR wing without ribs made in composite
Figure C.7: Net Resources for the high AR wing with ribs made in aluminium

Figure C.8: Net Resources for the high AR wing with ribs made in composite
Appendix D

Parametric Study

Figure D.1: Beam used to simulate the parametric study

Figure D.2: Maximum Tip Displacement for other configurations of the Cantilevered Beam