Development of a Cost Model for Novel Aircraft Configurations

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Abstract

In the aerospace sector there is a growing demand for new aircraft configurations and new materials. Nowadays, only minor improvements can be made to the most used aircraft configuration. Moreover, composite materials are increasingly sought after as substitutes for aluminium and, therefore, their implementation in this sector is growing. Consequently, the development of novel configurations is a necessary reality, as well as costs estimate at a preliminary design stage, so that decisions can be made on the financial viability of the investment. When developing a conventional aircraft, the parameters used in its cost estimate come from historical data. However, in the case of novel configurations, these parameters do not exist, requiring a new method for estimating costs. Thus, a process based cost model of automated tape laying (ATL) manufacturing is developed for different aircraft configurations considering relevant data of aircraft parts (geometry). In this way, the estimate of the production costs is possible. The model can also be adapted to different annual production volumes or to the capacity of the existing machines in a plant. In this thesis, a conventional aircraft and a joined wing are also analysed in relation to their production and aquisition phases. The production costs of both aircraft are obtained by the above mentioned model and then compared to each other. These data are still used in a sensitivity analysis with respect to the amount of material used, and in an investment appraisal.

Keywords: Cost model, ATL, Composites, Production Costs, Novel aircraft configurations

1. Introduction

The development of a cost model of an aircraft is a work for a team of engineers and designers of a company. This work of costs' estimation is complex due to the amount of relevant information and the preliminary phase of the prediction. It is on the design phase that all costs associated to the life cycle of the product should be estimated, being important the reliability of them. Production costs, operating costs and maintenance costs are some crucial costs that companies must have detailed in order to proceed with businesses, making suitable and affordable offers to their clients, the aviation companies.

This care about costs is important not only to manufacturers, but also to the aviation companies that, apart from lower acquisition prices of aircraft, could do a better finantial management of the company. Knowing the operating and maintenance costs, aviation companies will know how much each aircraft will consume and spend per flight and could also predict the maintenance cost.

Cost models are usually based on several cost estimation relationships developed by using historical data of variables which could be for example the empty weight, speed, wing area, power and production quantity [1]. The difficulty of a traditional cost modeling is the prediction for unconventional aircraft, for which no historical data is available and there are no cost estimation relationships validated.

2. Background

2.1. Life Cycle Costing

In order to validate investments, an analysis to all associated costs with expenditures during the life span is necessary. This analysis is called Life Cycle Costing (LCC) and it is also particularly useful for economic comparison of alternatives, giving the required technical and economic considerations to every aspect of the life cycle [2]. From the initial design of the product, costs and all subsequent expected costs are included in the calculations, as well as disposal value and any other quantifiable benefits to be derived.

The LCC is a method that benefits both the manufacturer and the consumer, in this case the airlines whose products are aircraft. On the one hand, the higher the perception of the associated costs by the manufacturer, the higher the control over them, optimizing the production, thereby increasing the companies' profit. On the other hand, on the costumer's side, the LCC is used as an evaluation technique that summarizes costs and relevant information on which it can be based an informed decision about investment, contributing to a logic and wise decision. The more information provided on the aircraft's life cycle, the easier it becomes for the operator to check if the aircraft fits his operational and economic strategy, as well as which methods may be better to operate it.

LCC can be divided into four phases: design, production, utilization and disposal phases [3].

2.2. Design for Cost

Competitiveness is fundamental to the equilibrium of markets and the need and the demand for new techniques, developments and innovations must be constant between companies. However, the benefits of these improvements are not always achievable due to the high financial investment of the project, and therefore these initiatives are usually set aside [4].

Through manufacturing cost estimations and predictions, designers can realize and find solutions to the economic problems related with the product and design more cost-effective systems, which will subsequently influence the feasibility of the project. Designers must have the knowledge and sensitivity of all product development processes, must understand economics, marketing and risk, and consider cost as a variable design of equal weight as other performance variables. Therefore, designers begin to have a responsibility for life cycle engineering, an area neglected until the 1990s in the design of aerospace systems [5].

2.3. Cost Estimation Techniques

Cost estimation is an important process in the design phase of aircraft production. Through this technique, a company is able to determine the selling price of its products and whether its investments are feasible or not. However, it is a difficult process due to the high amount of information used in the estimation models and the coverage of the required areas [6].

The costs of a product can then be generated by three methodologies: analogical method, parametric method and process based model.

The analogical method is a technique based on costs of similar products previously produced, historical relations, among which the analyst compiles the maximum of similarities between the products generating the estimate. However, despite being fast, this technique fails in terms of accuracy in estimating the final cost [7].

The parametric method is a methodology that uses Cost Estimation Relationships (CERs) based on historical data. A CER is a fundamental technique in estimating costs that establishes a mathematical relationship between two variables, a dependent and an independent. The dependent variable is the case study, in other words, the cost to be estimated, while the independent variable is the variable that predicts the other through a correlation between one or more parameters with a certain meaning. Generally, the relationship is based and developed through historical data to which a statistical technique is applied later, such as linear regression for example [8].

Finally, the last methodology is based on the decomposition of the production and manufacturing processes that will be executed in each component of the product through a Work Breakdown Structure (WBS), which has costs associated later, that when summed will generate the estimate of cost [9]. It is considered a process based cost model (PBCM) and the advantages of this method are the facility of analysing errors and identifying where the largest estimates deviations occur due to the separation of the final product into components and the facts that it does not require historical data and it is functional for both new or traditional technologies. This technique relates cost drivers directly to the processes involved in production and it is able to specify cost changes due to changes in product and process designs. However, the major disadvantage of this technique is the detailed information required for the various processes, such as number of labor hours, total material to be used, waste and others, which turn this technique time-consuming.

2.4. Composites

Metals, more specifically aluminum alloys, have been the most widely used materials in the aerospace industry since the 1930s, particularly in structural parts. The experience and knowledge acquired over the years has decreased its cost of manufacturing and maintenance, which is an advantage in the choice of aluminum for the manufacture of aircraft [10]. In addition, the levels of reliability and safety of the material are also high due to the historical use of aluminum alloys. Features as excellent mechanical and thermal properties and being easily shaped in machining are other advantages of metals [11]. However, there are some disadvantages compared to composite materials, such as the weight increase for a part with the same tensile strenght and the lower corrosion resistance.

The composite materials may be defined as a combination of two or more distinct materials, which results in a material with different mechanical properties when compared with the original properties of each initial material individually. Comparing with conventional materials, composites have highly appreciated properties in aircraft production. The high strength-to-weight and stiffness-to-weight ratios, the capacity to handle tension, that minimizes the need for maintenance due to fatigue, the reduced number of parts and fasteners used in the product assembly, the corrosion resistance and the extended product life are the main advantages [12]. In addition, it is still possible to produce specific composites, with certain stiffness and strength, suitable to withstand the stresses and tensions which part will be subjected to during its lifetime. The desired properties are achieved by the different orientations of the fibers, the number of plies and the percentage of resin used. Thus, it is possible not only to reduce the number of labor hours required for production and development, but also to ensure the reliability of the material. The major disadvantages of composite materials are the cost of acquiring the raw material and the fact that it is considered a new material, which implies qualification and safety acceptance by the competent authorities [13].

Actually, some examples of the use of composite materials in the case of commercial aircraft, are the Boeing 787 Dreamliner (Fig. 1) and the Airbus A350 XWB.

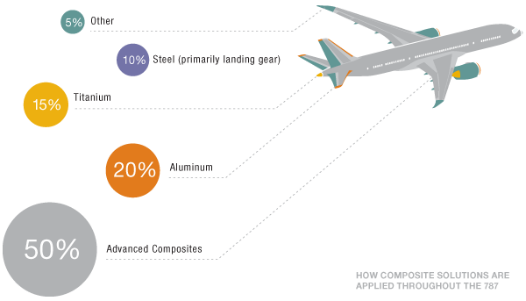


Figure 1: Distribution of materials applied to Boeing 787 [15].

2.5. Production Methods of Composites

In terms of production, composites can be manufactured by several methods, however only three will be described in a comparative manner: hand lay-up of prepreg, automated taping lay-up (ATL) and automated fiber placement (AFP). In both cases preimpregnated fibers are used, which require care not to lose their properties.

In the production process of an aerospace part in composite material, the application of glass fiber and copper is also a prevention, avoiding galvanic corrosion of the aluminum if fibers are in contact with the metal, and protecting the outer part of lightning strikes, respectively. Then, the process begins with the application of glass fiber and copper in the part mold, followed by the fiber placement according to the lay-up method and, finally, it is applied glass fiber once again. After the procedure, the part is sealed in a vacuum bag with a bleeder and a breather materials inside to absorb the excess resin and facilitate the absorption of air respectively. The curing process in the aerospace industry is usually performed in an autoclave, which, with increasing temperature and pressure, promotes a better finish to the part in terms of quality. At the end of production, finishing processes are performed followed by non-destructive tests to ensure that there are no defects [16].

The hand lay-up process of prepreg is a standard method in the manufacture of composites by the quality and high performance that can be acquired in the composites and by the adaptability of the process in the production of new parts [17]. It is an open molding method where specialized technicians manually lay layer by layer on the surface of the mold according to the orientation and sequence of the fibers up to the desired thickness.

Both ATL and AFP are composite manufacturing processes throughout the addition of material course by course. Unlike metal machining, which removes material, these processes are designated as additive manufacturing or inverse machining. In the case of ATL, the high productivity of large and flat parts is a consequence of the ability to lay-up large amount of material due to the width of the tape and the speed of the method. According to Hagnell [18], the lay-up rate varies between 10 to 150 kg of material per hour and depends on the size and the shape of the part. In the case of small parts, the ATL process significantly decreases its efficiency because the machine has to accelerate and decelerate rapidly along the path, failing to reach and work at the ideal laying-up speed. In turn, the material waste will also be higher given the amount of material placed in excess in each course performed.

The laying process is controlled by a Computer Numerical Control (CNC) system that commands the machine head and makes the placement of tapes of prepregs, thus eliminating the human errors observed in the hand lay-up process.

The AFP process is very similar to ATL, however, the main differences are the widths of the tapes placed, that are smaller, the fact that the machine head can distribute between 12, 24 or 32 tows of material simultaneously and the possibility of the system to be integrated in a robot, increasing the affordability of the process. This is a method that can produce curved, complex, contoured shapes and the variation of the number of tows of material depends on their complexity, which affects the productivity of the fiber placement. Two advantages about the distribution of material in different tows and the fact that each tow is independent to one another are its own production of complex parts and also the reduction of the amount of wasted material that varies between 2% and 5% [19].

2.6. Novel Aircraft Configurations

Nowadays, and for several decades, the most used aircraft either commercially or militarily is, as its name suggests, the conventional aircraft. Generally, the most common configuration, observed in most commercial aircraft, is the low wing cantilever monoplane with swept back trapezoidal wings of moderated aspect ratio and positive dihedral. However, one can also easily find conventional aircraft with high wing or zero swept angles for example. The concept of conventional aircraft is basically the identification of an aircraft with a main wing, a cylindrical fuselage and vertical and horizontal tails, a design studied for years, that thanks to the evolution of technology and sophisticated computational models has become increasingly efficient [20].

Currently, and according to experts in academia, industry and leading aerospace agencies, without a design change, this configuration only achieves incremental improvements in performance, fuel consumption and operative costs, which is not feasible with globalization and with the increase of air traffic observed in recent years. A major design change is therefore essential, new configurations are required to achieve new requisites and at the same time to reduce emissions, pollution and noise, thus contributing to a more sustainable environment [20]. One novel aircraft configuration is shown in Figure 2.

Figure 2: Joined Wing [21].

The Joined Wing is a novel aircraft configuration that is still being studied and under development. Its main characteristic is the connection of two wings. This new design is more structural and aerodynamically efficient and reaches the best range and the longest endurance in relation to any other type of configurations [20]. With its optimization, today the structural connection between the wings is made with the rear wing that has its root attached on the top of the vertical tail and the tip that sweeps forward to join the trailing edge of the main wing.

3. Cost Model Development

Although the most used material in the aerospace industry is aluminium due to its advantages in terms of mechanical and thermal properties, wide experience and good machinability, composite materials have become increasingly appreciated in the sector. Their advantages in terms of strength-to-weight and stiffness-to-weight ratios, corrosion resistance, capacity to handle tensions, the reduced number of parts and fasteners used in the product assembly and the extended product life make composites a viable option for the future, and consequently, they are the type of material implemented in this production model.

From the three composite production methods described in Subection 2.5, ATL is the method selected for this model, not only for its advantages of high productivity of large and flat parts (due to the high deposition of material) but also due to the cost of material used by ATL machine which is lower when compared with the one used in the AFP machine. The hand lay-up and AFP methods are then discarded.

In regard to estimation techniques, analogical and parametric methods are fundamentally based on historical data to develop cost estimations, which makes it impossible to estimate novel aircraft configurations' costs. A process based cost model (PBCM) is then developed through the decomposition of the necessary processes for the production of parts by ATL. The cost estimate is generated associating all costs related to each process. The advantages of this process are that it does not require historical data and it is a functional method for both novel and conventional aircraft configurations.

3.1. Processes

The PBCM is developed by decomposing the manufacturing method, as shown in Fig. 3. This method can be divided into seven phases, which individually correspond to a particular production process. The assembly phase, as already mentioned, is not included in the cost model, since this is a preliminary model of production costs. Any kind of prior and/or post-production costs are not included in this template.

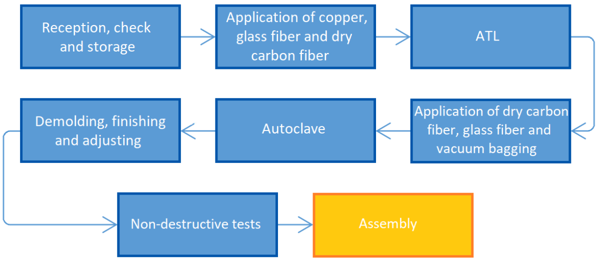


Figure 3: Processes of the manufacturing method.

In the developed cost model, each process of the manufacturing method receives a set of inputs and returns the outputs. The outputs of each phase are the costs of the process, that when finally added, lead to the production cost estimate of the part.

3.2. Inputs

In order to develop the cost model, it is necessary to introduce several types of inputs. They can be divided into four groups: exogenous, material, process and part data.

The first group of inputs, named exogenous data, are common inputs for all processes that are dependent on the operation and organization of the company.

The material data is dependent on the type of material used in the deposition phases. Four types of materials are defined: copper, glass fiber, dry carbon fiber (these three used in the second and fourth phase) and prepreg carbon fiber (used in the fiber placement by ATL machine, which corresponds to the third phase).

The specific inputs of each of the seven processes, which vary in value according to the characteristics and needs of each of them, are called the process data. There are inputs related to the characteristics of the process that define its quality, such as the percentages of pass, scrap and rework, inputs related to process-infrastructure and inputs related to the downtime information of the production line. All periods of a production line can be observed in Fig. 4.

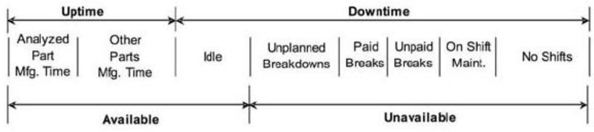


Figure 4: Production line.

Finally, there are the inputs related to the parts, namely geometric characteristics of parts and their production volumes. The cost model should receive as inputs the geometry of each part that will be produced. However, the data that is provided by MDO framework developed by the IST Aerospace Group arrives through coordinates of points, dimensionless relations and percentages. To convert these data into the desired inputs, linear interpolation between the coordinates and some geometric calculations are required.

3.3. Intermediate Calculations

This subsection demonstrate some intermediate calculations about material and time, two main cost drivers of this cost model. The presented variables are fundamental to cost analysis and important to the model development.

There is a percentage of pass that causes a reduction of the number of parts obtained at the end of each production process compared to the number of parts initially inserted. Thereby, it is necessary to produce a production volume greater than the desired volume at the end. It is a calculation based on the objective. The initial production volume decreases throughout the processes and the number of parts required in each process can be given by Eq. 1.

$$Number\ of\ Parts_i = \frac{Number\ of\ Parts_{i+1}}{\%\ Pass_i + \%\ Rework_i \cdot \%\ Rework\ Pass_i}\,. \quad (1)$$

Other important variables to this cost model (related to material) are the parts weight, the number of layers per part according to the desired thicknesses and the percentages of technical scrap during the ATL process.

Regarding the other cost driver (time), cycle time is another important variable to the cost model and it is presented below.

$$Cycle\ Time = Setup\ Time + Machine\ Time\,. \quad (2)$$

In a process, the cycle time is given by the sum between setup time and machine time. The setup time represents the preparation time required before machining and it is a constant input, independent of the size of the part to be produced. The machine time is the time that the machine takes to carry out the process, being therefore a variable that depends on the part size and/or on the speed of the machine during the process.

Regarding to the ATL process, the machine time is calculated through a lay-up rate obtained by Lukaszewicz [22], which increases logarithmically with the increase of the part surface area. The result of the study can be seen in Fig. 5.

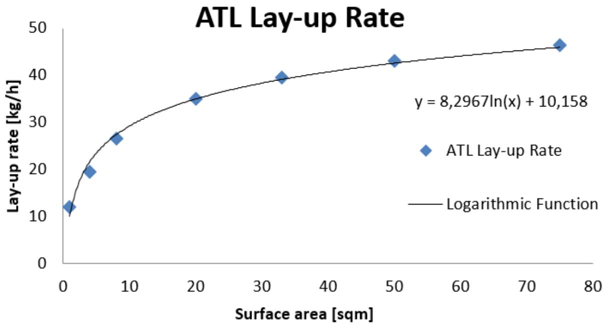


Figure 5: ATL lay-up rate [22].

With cycle times of each part and with the number of parts to be produced in each process, it is possible to calculate the time required for the production of all types of parts in each process, equivalent to the uptime. Then, it also possible to calculate the allocation percentages.

3.4. Costs

In each process, costs are divided into variable and fixed costs.

The annual variable costs depend mainly on the production volume, however, these costs per part are approximately constant. These costs can also be divided into material, scrap, labor, overhead and energy costs.

The material cost represents the value of the materials used in the production of parts. This cost takes into account the value of the materials required in both the production and necessary rework, and also the value of the consumables spent during the process.

Scrap cost represents the amount spent to remove the wasted material. Unlike metals, the composite material is very difficult to be recycled due to the high costs of chemical separation. Thus, wasted material is converted into a cost to be dumped.

Labor cost represents the payment of employees who work directly on the production line.

Overhead costs are also variable costs associated with workers. However, these workers are indirectly related to the product operation. They are usually from engineering, administration or support areas.

The last variable cost introduced in this model is the energy cost. This expense represents the amount of money spent in energy consumption during the process and depends on the cycle time of each part, the number of parts to be produced, the power consumption of the machine and also the cost of the energy unit (€/kW.h).

Fixed costs are calculated by allocating an annual cost as an annuity of the investment and are constant as long as the plant structure does not vary. They are constant costs on an annual scale and, therefore, the larger the production volume, the lower the unit cost of production.

Depending on the type of investment under study, fixed costs can be related to main machine, tooling, building and maintenance. Eq. 3 demonstrates how to calculate any fixed cost type.

$$Fixed\,Cost_i = Investment_i \cdot \left[\frac{Interest}{1-(1+Interest)^{-Lifetime}} \right] . \quad (3)$$

In this equation, it is considered a fixed interest rate and also a lifetime that can be related to the equipment, buliding or the production period, according to the fixed cost that is being analyzed.

4. Test Cases and Results

In order to carry out the test cases, two aircraft configurations for the regional segment were developed in the MDO framework from the IST Aerospace Group. The first configuration is based on a conventional aircraft model, a low wing cantilever monoplane with swept back trapezoidal wings of moderated aspect ratio and positive dihedral. The second configuration is based on a novel aircraft configuration, a joined wing, in which the rear swept forward high wing joined the front swept back low wing near its tip. Both of them were designed to achieve the same requirements and due to that, there are some similarities between them. Because the objective is a comparison of production costs, only different parts were assumed to be relevant for the study. The parts that are equal, such as engines and fuselage, are not integrated. Therefore, only the main wing, rear wing, horizontal tail a vertical tail will be evaluated for having different dimensions and thicknesses.

4.1. Production costs considering the production at maximum capacity

In this first analysis, the aim is to determine the maximum annual production volume that a plant can produce for the conventional and the joined wing aircraft.

It is assumed that there is a plant equipped with a specific machine in each process and a reception, check and storage space of 150 m^3, equivalent to three machines of this process, an exception justified by the need for sufficient space so that there is no problem with the amount of material storage.

With the number of machines defined, it is intended to determine the annual production volume of each aircraft. The results are 26 units for conventional aircraft and 14 units for joined wing. These annual production volumes were obtained by maximizing the machine use.

After the annual production volumes being determined, aircraft production costs can be finally obtained, as can be observed in Fig. 6.

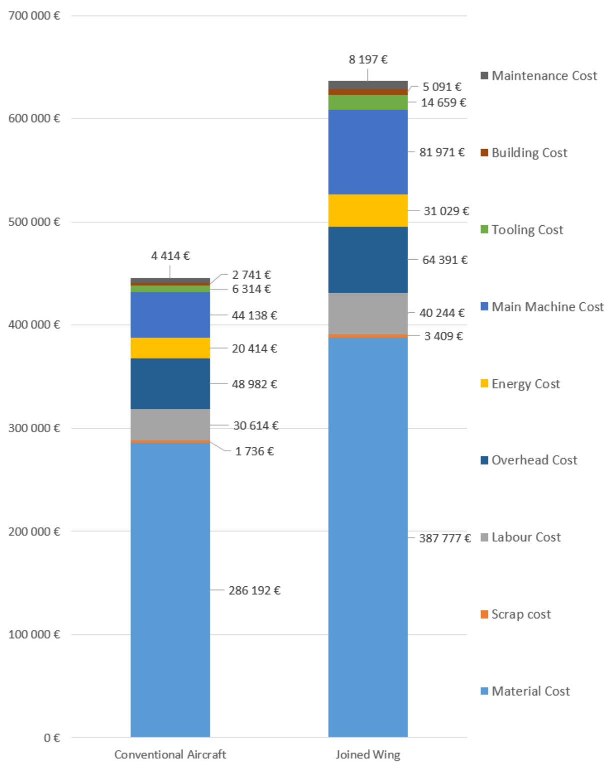


Figure 6: Production costs of the first analysis.

It is verified that the conventional aircraft has a production cost inferior to the production cost of the joined wing. By adding the different cost values presented, it is obtained a production cost of 445 548 € for conventional aircraft and 636 768 € for joined wing. The cost difference between both aircraft is 191 220 €.

Comparing the graphs, it is verified that the biggest difference is registered in the material cost (more than 100 000 €), which is due to the fact that joined wing requires more material for its parts production. In addition, the scrap cost is also higher in the joined wing case for the same reason. If there is more material to be used during production, the greater the amount of scrap to be produced. Regarding labor, overhead and energy costs, with more material and more working hours being required for the production of joined wing, the higher the costs compared to the conventional aircraft.

Relatively to fixed costs, cost differences are subject to the fact that the annual cost is allocated according to the number of aircraft produced. Since the annual production volume of conventional aircraft is higher than joined wing, the fixed costs per unit are lower.

4.2. Production costs considering an annual production volume of 50 aircraft

In this second analysis, it is assumed that the plant has an annual production volume of 50 aircraft, a value based on the annual production of an aircraft used for regional flights, such as the aircraft of this study. Taking this as a premise, it is necessary to determine the number of machines per process, to obtain the production costs of conventional aircraft and joined wing.

Regarding the number of machines per process, this was determined by taking into account their production capacity. In the case of conventional aircraft, two machines are required in each process (excluding the reception, check and storage process where it was, once again, assumed a space of $150m^3$, equivalent to three machines of this process, so that there is no problem regarding the lack of space for material storage), and in the case of joined wing, it is verified that the number of machines in some processes must be greater than two to ensure the production volume.

With the production volumes and the number of machines per process defined, the production costs of the aircraft can be determined (shown in Fig. 7).

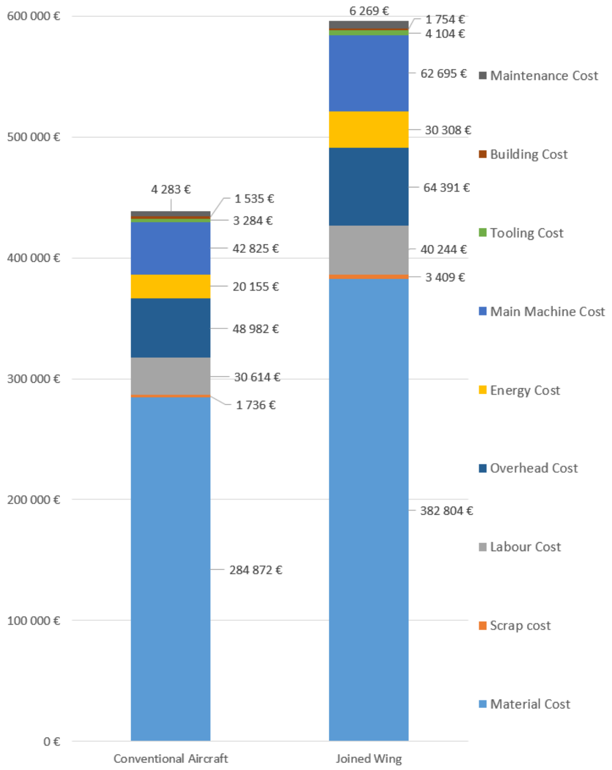


Figure 7: Production costs of the second analysis.

It is concluded, once again, that the production cost of the conventional aircraft is lower than the production cost of the joined wing. According to the obtained results, it is achieved a production cost of 438 286 € for the conventional aircraft and a production cost of 595 978 € for the joined wing. The difference between both production costs is 157 692 €.

Similar to the first analysis, it is verified that the variable costs of the joined wing are superior to those of the conventional aircraft. Both material and scrap costs are higher because the joined wing needs more material for its production. The labor, overhead and energy costs are also higher due to the increase in the number of working hours.

In regard to fixed costs, since the annual production volume is the same (50 aircraft), if both plants had the same number of machines, the costs would be similar. However, the number of machines required to produce the 50 joined wings is higher than the number of machines required to produce the 50 conventional aircraft. Thus, as can be seen in Fig. 7, all fixed costs of the joined wing are higher than the fixed costs of the conventional aircraft.

Comparing the values obtained in this analysis with the values obtained in the previous one (Subsection 4.1), it can be seen that the production costs of both aircraft are lower in this second analysis. Analysing the results, it can be seen that the variable costs per aircraft are very similar and that the fixed costs are the ones that decrease the total production cost of the aircraft. Although in the second analysis there is a larger number of machines per process, the annual production volume is also higher, significantly reducing the fixed costs per aircraft, which leads to lower total production costs in this second analysis. This is equivalent to what happens in an economy of scale: the larger the number of units to be produced, the lower the unit production cost.

4.3. Sensitivity Analysis

In this section, a sensitivity analysis of the production cost is carried out with respect to the thickness of the parts that constitute the aircraft. The objective is to analyse the impact that a reduction in the number of layers of composite material has on the final production cost of an aircraft.

For this analysis, the example used is the joined wing. It is decided to remove two layers of composite material on all aircraft parts, since if only one layer of material were removed, symmetry problems could occur and the material properties would be altered. It is verified a reduction of 171.79 kg in composite material.

However, this reduction does not only diminish the material cost. Reducing the number of layers of composite material also decreases the number of hours required to produce the parts, which is essential for the reduction of labor, overhead and energy costs.

The production cost of the new joined wing is lower (approximately 20 000 €) when compared to the joined wing of the previous analyses.

4.4. Investment Appraisal

Assuming that an airline intends to invest in an aircraft and exists the possibility to choose between a conventional aircraft or a joined wing, through this assessment it is possible to verify the moment from which one investment becomes profitable when compared to the other.

The desired aircraft will be used for regional flights with a range of 1400 km and with a mission profile equal to the one shown in Figure 8. In addition, the aircraft is expected to perform two daily flights, 300 days a year, equivalent to a total of 600 flights per year.

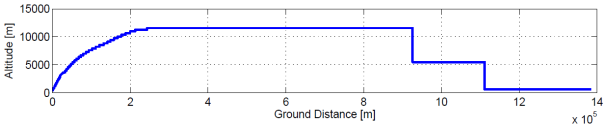


Figure 8: Mission profile.

This mission profile is divided into six segments: climb, cruise, first descent, alternate, second descent and hold. Note that the descent phases were assumed to be neglible in terms of fuel consumption.

The factors taken into account in this investment appraisal are the differences in production costs and jet fuel consumption of each aircraft.

From the MDO framework, it is obtained the consumptions of jet fuel per segment, in kilograms, which are presented in Table 1.

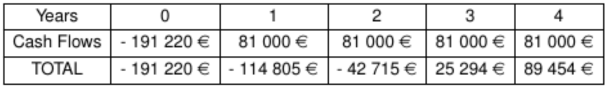
Table 1: Jet fuel burned in quilograms.

	Conventional Aircraft	Joined Wing
Climb	458 kg	414 kg
Cruise	775 kg	598 kg
Alternate	239 kg	172 kg
Hold	500 kg	529 kg
TOTAL	1972 kg	1713 kg

As can be seen, the joined wing consumes less fuel than the conventional aircarft. The fact that the joined wing is heavier causes a higher angle of attack during its mission, which results in a drag increase. However, this problem is compensated by the reduction in induced drag due to the reduced wing area that produces lift (aspect ratio increase), associated to the wings of the joined wing, which reduces fuel consumption. When the aircraft is flying at lower speeds, as in the hold segment, the drag reduction is not so significant, leading to an increase in fuel consumption during this segment, as shown in the table.

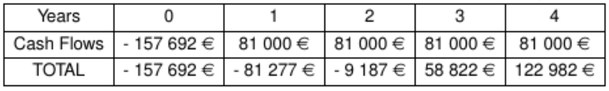
The net present value is the sum of all discounted cash flows associated to a time period at a given discount rate. It is used an interest rate of 6%, an assumed value in the aerospace sector, according to [23]. The initial cash flow ($t = 0$) is the difference in production costs between both aircraft, considered negative, since it is an initial expense that will be subsequently discounted by the following cash flows, which results from savings in fuel consumption. Assuming that 600 flights are performed per year, and knowing that the savings in each flight is 135 €, cash flows of 81 000 € are obtained per year.

Table 2: Net present value of the first analysis.



Years	0	1	2	3	4
Cash Flows	- 191 220 €	81 000 €	81 000 €	81 000 €	81 000 €
TOTAL	- 191 220 €	- 114 805 €	- 42 715 €	25 294 €	89 454 €

Table 3: Net present value of the second analysis.



Years	0	1	2	3	4
Cash Flows	- 157 692 €	81 000 €	81 000 €	81 000 €	81 000 €
TOTAL	- 157 692 €	- 81 277 €	- 9 187 €	58 822 €	122 982 €

In both analyses, the payback periods are short, between the second and third years. It is concluded that despite having to spend more money on the joined wing production, in a few years the return of this investment is recovered.

In this investment appraisal, as mentioned above, the only factors considered are the differences between the production costs and the fuel consumptions of the aircraft. However, there are other factors that could have entered into this assessment, such as aircraft maintenance and overhaul costs, other flight operating costs and environmental costs. The first factor referred would benefit the choice of conventional aircraft, since this one is the most used today, and there is a greater maintenance experience, implying lower maintenance costs. On the other hand, environmental costs would benefit the choice of joined wing since the economic costs at this level (regulations, standards) are lower compared to conventional aircraft.

5. Conclusions and Future Work

The aim of this thesis was to develop a process based cost model of automated tape laying (ATL) for novel aircraft configurations. It is concluded that this model is versatile since it can also give an estimate of the production costs of conventional aircraft, since model inputs are entered in the form of parts' geometry. The model can also be adapted to different annual production volumes or to the capacity of the existing machines in a plant. The cost estimate obtained presents the fixed and variable costs of an aircraft production.

From the test cases analysed in this thesis, it is concluded that the joined wing has higher production costs than the conventional aircraft. Costs related to the rear wing and vertical tail are higher than the costs of horizontal and vertical tails of conventional aircraft. The fact that the rear wing is larger and requires more material in its production, and the fact that this structure is long and narrow, which leads to several wastes of material during the ATL process, contribute to the increase in the joined wing production cost. In relation to its vertical tail, it needs a more robust structure due to have to support the rear wing weight, which implies a greater deposition of material and consequently an increase of its cost. Unlike these structures, the cost of the main wing in the joined wing is lower: this main wing has smaller area due to the fact that the rear wing also produces lift.

In these test cases, aircraft fuselage and engines were not contemplated, since these structures are the same for both aircraft and, therefore, their costs have no impact on the comparative analyses performed.

It has also been found that the majority of the production costs, about 60 to 65% of the total value, comes from the material costs, material which was used in the production of the parts.

Through an investment appraisal, it was observed that the difference in the production cost of the joined wing when compared to conventional aircraft can be compensated after two to three years, taking into account only the fuel consumption, which in this configuration (joined wing) is lower.

A sensitivity analysis of production costs was also carried out by reducing the number of layers of composite material applied to the aircraft. This removal has led to a reduction in these costs, not only in terms of material cost, but at all types of variable costs (scrap, labor, overhead and energy costs), since the removal of layers diminishes the number of working hours. It can further be concluded that if the number of layers of composite material to be removed was higher, the number of machines required could decrease or the annual production volume could increase, leading to a reduction in fixed costs.

A few suggestions for future work are proposed below.

The cost model developed in this thesis is a versatile and flexible model, allowing variety in the type of inputs introduced. Thus, it is possible that this model can be applied in a financial analysis of several types of configurations, and not only in the two test cases in this thesis (conventional aircraft and joined wing). However, the model is limited with respect to the production method, allowing only the use of composite material and ATL.

It should be taken into account that this cost model still requires the insertion of inputs manually, which makes their use time-consuming. This can be one of the points to improve in the future, making this process more automatic and easy to handle.

Worth to note that this is a preliminary model of production costs, excluding any previous or subsquent phases, such as the assembly phase. Thus, the model can be developed, making it comprehensible to the other phases mentioned.

In addition, in the test cases, only production costs of wings and tails are considered, and the production costs of an entire aircraft are not accounted. In this way, there is the possibility of carrying out a more reliable financial analysis taking into account the higher possible number of parts of an aircraft.

References

[1] J. Ritschel. A comparative analysis of the cost estimating error risk associated with flyaway costs versus individual components of aircraft. Master's thesis, Air Force Institute of Technology, March 2003.

[2] L. Keys. System life cycle engineering and DF'X'. *IEEE Transactions on Components, Hybrids and Manufacturing Tecnhology*, 13(1):83–93, March 1990.

[3] Y. Asiedu. Product life cycle cost analysis: State of the art review. *International Journal of Production Research*, 36(4):883–908, 1998.

[4] A. Velocci. Profit wave uncovers nagging paradoxes. Aviation Week and Space Technology, May 1995.

[5] Defense Manufacturing Council (DMC) Executive Group off-site meeting notes, January 1995.

[6] S. Zijp. Development of a life cycle cost model for conventional and unconventional aircraft. Master's thesis, Delft University of Technology, June 2014.

[7] A. Niazi and J. Dai. Product Cost Estimation: Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128:563–575, May 2006.

[8] O. Younossi and M. Kennedy. *Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes*. Monograph Reports. Rand Corporation, 2001.

[9] U.S. Air Forces Systems Command. AFSC Cost Estimating Handbook Series, 1986.

[10] G. Marsh. Composites flying high. *Reinforced Plastics*, 58(3):14–18, 2014.

[11] V. Songmene and R. Khettabi. *Aluminium Alloys, Theory and Applications: Machining and Machinability of Aluminum Alloys*, chapter 18, pages 377–400. InTech, 2011.

[12] Lockheed Martin. Advanced Composite Cargo Aircraft (ACCA). Online, May 2017. https://lockheedmartin.com/us/products/acca.html.

[13] G. Marsh. Aerospace composites - the story so far. *Reinforced Plastics*, 40:44–48, 1996.

[14] D. Lambert. Composite aircraft life cycle cost estimating model. Master's thesis, Air Force Institute of Technology, March 2011.

[15] J. Hale. Boeing 787 from the Ground Up. Boeing Aeromagazine, 2008.

[16] U. Singh and M. Dwivedi. *Manufacturing processes*. New Age, 2009.

[17] J. Hinrichsen. The challenge of reducing both airframe weight and manufacturing cost. *Air & Space Europe*, 3:119–121, 2001.

[18] M. Hagnell. A composite cost model for the aeronautical industry: Methodology and case study. *Composites: Part B*, 79:254–261, 2015.

[19] D. Lukaszewicz and C. Ward. The engineering aspects of automated prepreg layup: History, present and future. *Composites: Part B*, 43:997–1009, 2012.

[20] R. Cavallaro and L. Demasi. Challenges, Ideas, and Innovations of Joined-Wing Configurations: A Concept from the Past, an Opportunity for the Future. *Progress in Aerospace Sciences*, 87:1–93, 2016.

[21] Lockheed Martin. NASA Environmentally Responsible Aviation. Online, May 2017. https://www.lockheedmartin.com/en-us/index.html.

[22] D. Lukaszewicz. *Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates*. PhD thesis, University of Bristol, 2011.

[23] D. Tomas. Melhoria do processo de controlo de qualidade na fuselagem central de uma aeronave militar. Master's thesis, Instituto Superior Tecnico, April 2017.