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Bottom-Up Manufacturing Cost Optimisation of Composite Aircraft Structures: Manual Layup vs. Automated Layup

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Abstract. This paper presents a novel methodology for the bottom-up manufacturing cost optimisation of composite aircraft structures for Automated Fibre Placement (AFP) techniques. The proposed bottom-up approach divides the manufacturing process into many individual activities, making it applicable to a wide range of composite aircraft structures. This approach also splits the costs into material, tool, machine, labour, and indirect costs, enabling the precise cost analysis of these structures. A numerical example, featuring a mono-stiffener composite panel, is investigated. The manufacturing cost of manual layup is compared against that of automated layup. Results indicate that manual layup is superior, in terms of cost, for the manufacture of the mono-stiffener composite panel, and that the safety of the panel can be significantly improved with only a small 5% increase in manufacturing costs.

INTRODUCTION

If a component can be designed with low manufacturing costs and without compromising on safety, it can have a significant impact on the extremely competitive aviation market. This is especially important for composite aircraft parts. Although composite materials have demonstrated their superiority, in terms of weight and mechanical properties, over more traditional materials, such as aluminium, their use is often limited due to their relatively high costs. For composites to become more widely used in the extremely competitive aviation market, accurate estimation of the manufacturing costs of composite aircraft parts, and a better understanding of how safety influences these costs, is essential to any aircraft manufacturer.

Manual Layup (ML), or hand lay-up, whereby composite prepreg plies are laid up by hand to create a composite structure, is commonly used in the aviation industry for creating simple composite structures. However, for more complex composite structures, such as larger structures or structures with complex shapes, manual layup becomes impractical. Automated Fiber Placement (AFP) is a manufacturing technique that is capable of creating complex composite structures at higher speeds, and with greater control, than manual layup [1]. The fiber in AFP comes in the form of a 'tow', a bundle of fibres impregnated with epoxy resin. AFP machines precisely lay down these tows to build up the structure. Due to the increasing use of composites in the aviation industry, and the complex shapes often found in aircraft structures, AFP has been increasingly used in the aviation industry over the past few decades. Specialised AFP machines, enabling a high rate of production and high quality, have been created specificially for commerical aircraft production [1].

Many previous works have developed approaches for modelling the costs associated with layup techniques [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. One notable example is Hagnell et al. [19] where a cost modelling methodology was developed to model the costs associated with ML, AFP and Automatic Tape Layup (ATL), an alternative to AFP that uses tapes instead of tows. The proposed methodology was successfully applied to a composite aircraft wing cover. Hagnell et al. [18] later successfully extended this costing methodology to a composite wing box. In his thesis, Haffner [26] developed detailed costing methodologies for composite structures creating using ML, AFP, and ATL. Morse et al. [27] developed a costing methodology for ML, and applied it to a composite aircraft fuselage panel.

If a structure can be manufactured at low cost, while also demonstrating good structural performance, it can have a significant impact on the aviation industry, and there are many relevant examples in the literature of this [28, 29, 30, 31, 32, 33, 34]. A notable example is Chakri et al. [33] which presented a directional bat algorithm for optimising the welding cost of a beam structure. Fang et al. [34] developed a time-variant methodology also for optimising welding cost. Beck et al. [31] optimised the manufacturing cost of a three-bar structure and a built-up column. Dersjo et al. [30] developed a methodology for optimising the manufacturing cost of a steering gear component from a heavy duty truck. Finally, Morse et al. [27] developed a detailed methodology for optimising the structural reliability and manufacturing cost of a composite aircraft fuselage panel manufactured using ML. Many of the above works have developed methodologies involving ML, but none have involved AFP or ATP. Since these techniques are becoming

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more and more common in the aviation industry, it is very important to a develop a methodology that balances the optimisation of structural performance with the optimisation of the manufacturing costs associated with AFP or ATP, with the goal of designing a structure that performs well but also can be manufactured at low cost.

In summary, this work aims to build upon the work conducted in [27] and develop a novel methodology for optimising the structural performance and the manufacturing costs of composite aircraft structures fabricated using AFP.

The layout of the paper is as follows: The methodology for the comprehensive bottom-up manufacturing cost estimation of AFP for composite aircraft structures is described in section . A numerical example featuring a mono-stiffener composite panel from an aircraft fuselage subjected to buckling is presented in section .

MANUFACTURING COST MODELLING

The manufacturing cost of a part C_{part} is a function of the cost of the n individual activities used in the manufacture of the part:

$$C_{part} = \sum_{i=1}^{n} C_{act_i} + C_{ind} \tag{1}$$

where C_{act_i} is the direct cost of the i^{th} activity, and includes material, machine, tool, and labour costs. n is the number of activities. C_{ind} are the indirect costs and includes costs such as facility costs and indirect labour costs, and can be calculated as a percentage of the total activity costs:

$$C_{ind} = \frac{\%_{ind}}{100} C_{part} = \frac{\%_{ind}}{100 - \%_{ind}} \left(\sum_{i=1}^{n} C_{act_i} \right) \tag{2}$$

where $\%_{ind}$ is the indirect cost percentage and is typically around 10% [25]. Therefore:

$$C_{ind} = 0.1 C_{part} = 0.11 \left(\sum_{i=1}^{n} C_{act_i} \right) \tag{3}$$

The cost of the i^{th} activity can be written in terms of its material costs C_{mat_i}, tool costs C_{tool_i}, machine costs $C_{machine_i}$, and labour costs C_{lab_i}:

$$C_{act_i} = C_{mat_i} + C_{tool_i} + C_{machine_i} + C_{lab_i} \tag{4}$$

A detailed breakdown of how to estimate C_{mat_i}, C_{tool_i}, $C_{machine_i}$, and C_{lab_i} can be found in [27].

Automated Fiber Placement (AFP) Cost Modelling

The cost of using AFP is a function of the materials used in AFP and the cost associated with using the AFP machine.

The material cost C_{mat_i} is a function of the unit costs the materials $C_{unit\_mat_j}$, the quantity of the materials Q_{ij}, and the percentage of this quantity that is wasted during manufacture $\%_{waste_j}$:

$$C_{mat_i} = \sum_{j=1}^{m} C_{unit\_mat_j} Q_{ij} (1 + \%_{waste_j}) \tag{5}$$

where m is the number of materials used in the i'th activity.

The units costs and waste percentages of the composite prepregs used in ML and AFP are presented in Table 1. These unit costs were chosen based on data found from a variety of sources: previous research studies concerning

TABLE 1: Common materials involved in composite manufacturing. Their typical unit costs and waste percentages are shown.

Material	**Unit cost**	**Waste** (%)
Composite prepregs	53.27 €/kg	20
Composite prepreg tows	117.18 €/kg	4

the manufacturing cost of aerospace composite parts [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26], commercial websites, and information provided by our industry partner *Plyform Composites Srl* a company specialising in the manufacturing and assembly of advanced composite materials. The unit costs have been converted to Euros and adjusted for inflation. AFP, being an automatic technique, typically has a lower waste percentage than ML, but a higher unit cost due to the use of prepreg tows.

The machine cost C_{mac_i} associated with AFP is a function of the acquisition cost of the AFP machine, known as investment cost, the power usage cost of the AFP machine, and the time required by the AFP machine to create a layup. Based on previous studies, the investment cost of the AFP machine is approximated at 2,700,000 €with an amortization period of 10 years. The power consumption is estimated at 100 kW with a cost of 0.1€/kWh. The AFP machine is assumed to be in use for 3 shifts a day, 8 hours per shift, for 240 work days per year. The time required by the AFP machine to create a layup is assumed to be a function of the quantity of the j^{th} prepreg material Q_{ij} (kg), the deposition rate D_{rate} (kg/hr), and the time required to set-up the AFP machine t_{setup}:

$$t_i = \frac{Q_{ij}}{D_{rate}} + t_{setup} \tag{6}$$

Based on previous studies and data provided by our industry partner, it is estimated that D_{rate} = 45kg/hr and t_{setup} = 1hr.

When laying-up complex shapes with AFP, such as a stiffener, a process known as Hot Drape Forming (HDF) needs to be used. In this process, AFP is used to create the layup on a flat mould. This flat layup is then placed over a stiffener-shape metal block, and subjected to a vacuum and heated to a low temperature (50-60°C). This causes the resin the soften and allows the layup to take the form of the stiffener.

The cost associated with HDF is a function of the investment cost of the HDF machine, the time required by the HDF machine to form the layup, and the labour cost associated with moving the flat layup to the HDF machine and setting up the machine. Based on previous studies and data provided by our industry partner, the investment cost of the AFP machine is approximated at 160,000 €with an amortization period of 10 years. The power consumption is estimated at 25 kW with a cost of 0.1€/kWh. The HDF machine is assumed to be in use for 3 shifts a day, 8 hours per shift, for 240 work days per year. The labour time associated with moving the flat layup to the HDF machine and setting up the machine is around 0.3 hours. The time required by the HDF machine to form the layup is around 0.5 hours.

NUMERICAL EXAMPLE

To demonstrate the proposed methodology, a numerical example featuring the composite mono-stiffened panel seen in Figure 1 is investigated. The composite mono-stiffened panel is composed of two parts: the skin and the stiffener. It is subjected to a compressive load of 10 kPa parallel the stiffener on one side, and clamped on the opposite side. The design of the panel is to be optimised in terms of manufacturing cost and its resistance to buckling.

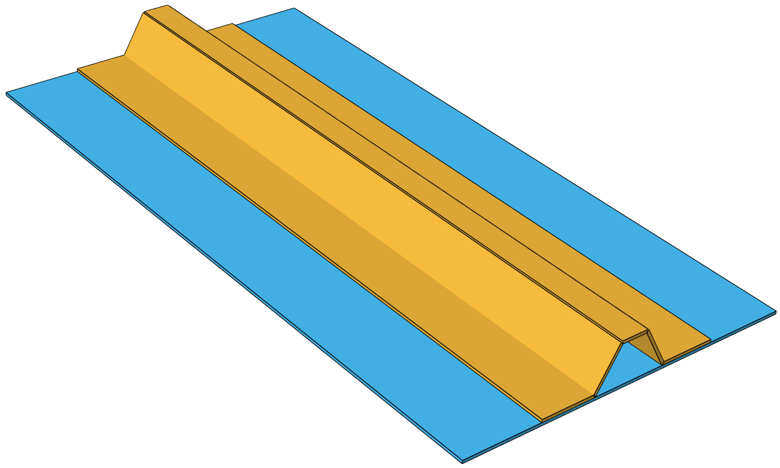

FIGURE 1: The stiffened composite panel used in the numerical example.

The dimensions of the skin and stiffener can be seen in Figures 2 and 3 respectively. The design parameters in the optimisation are the dimensions of the stiffener: d_1, d_2, d_3, and d_4, as shown in Figure 3. Both the skin and the stiffener have the layup $[+45/-45/0/0/90/0]_s$ with a ply thickness of 0.184mm, for a total thickness 2.208mm. The composite prepregs used in both parts have the properties $E_1 = 140$GPa, $E_2 = E_3 = 8.7$GPa, $G_{12} = G_{13} = 4.3$GPa, $G_{23} = 3.1$GPa, $\nu_{12} = \nu_{13} = 0.31$, $\nu_{23} = 0.40$, and mass density $\rho = 1400$ kg/m^3.

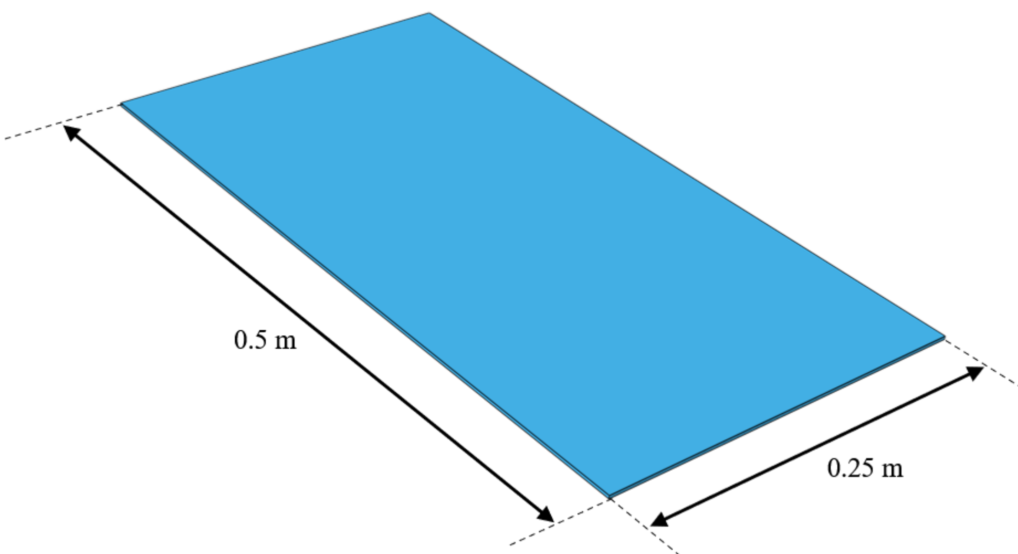

FIGURE 2: The geometry of the skin.

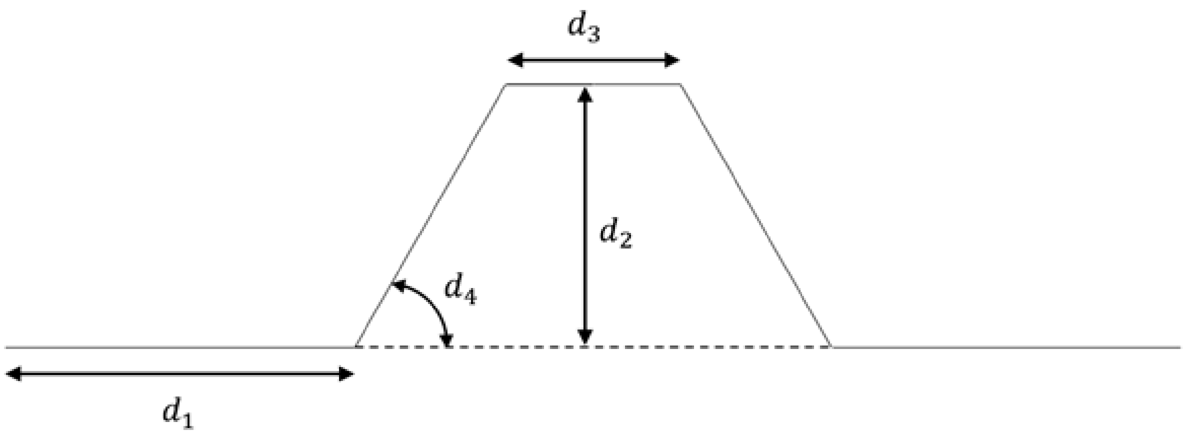

FIGURE 3: The geometry of the stiffener. The four design variablesare shown.

A Finite Element Method (FEM) model was created of the composite stiffened panel in Abaqus FEA. The FEM model is composed of 575 (325 on the skin, and 250 on the stiffener) quadrilateral elements of type S8R, as this was found to provide convergence in the value of B_{min}. The average time to complete an analysis was 20s on a computer with an 8-core 3.59GHz processor.

Multi-Objective Optimisation

The optimisation problem is defined as:

$$\begin{aligned} &\text{Minimise:} && Cost(\mathbf{d}) \\ &\text{Maximise:} && B_{min}(\mathbf{d}) \\ &\text{Subject to:} && \mathbf{d}^L \leq \mathbf{d} \leq \mathbf{d}^U, \quad \mathbf{d} \in \mathbb{R}^{n_d} \end{aligned} \tag{7}$$

where $\mathbf{d} = [d_1, d_2, d_3, d_4]$ is the vector of design variables, and $n_d = 4$ is the number of design variables. B_{min} is the minimum buckling load of the panel and describes its buckling resistance. A higher value of B_{min} means that the buckling resistance of the panel is higher. The details of these design parameters can be seen in Table 2.

TABLE 2: The details of the design parameters.

Design parameter	Minimum	Maximum
d_1	10 mm	30 mm
d_2	10 mm	50 mm
d_3	10 mm	30 mm
d_4	50°	70°

NSGA2 (Non-dominated Sorting Genetic Algorithm) is used to solve equation (7). In NSGA2, each objective is treated independently and a Pareto front is created. On the Pareto front, reducing cost is impossible without also reducing buckling performance.

Bottom-Up Manufacturing Cost Estimation

The stiffened panel is manufactured as shown in Figures 4 and 5. A co-curing assembly procedure is used for the assembly. In this procedure, the wet layup (the layup has not yet been cured) of the stiffener is placed onto the wet layup of the skin, while the skin is still in its mould. From an industry point of view, the manufacture of the stiffener panel is a single workflow from the skin, and the stiffener is added in the assembly stage. The details of these activities can be found in [27].

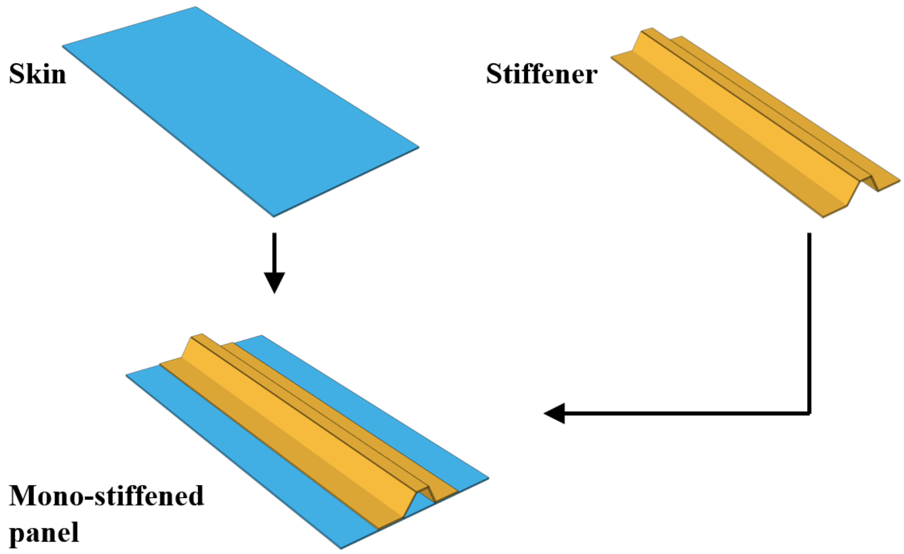

FIGURE 4: Flowchart showing the assembly of the stiffened panel.

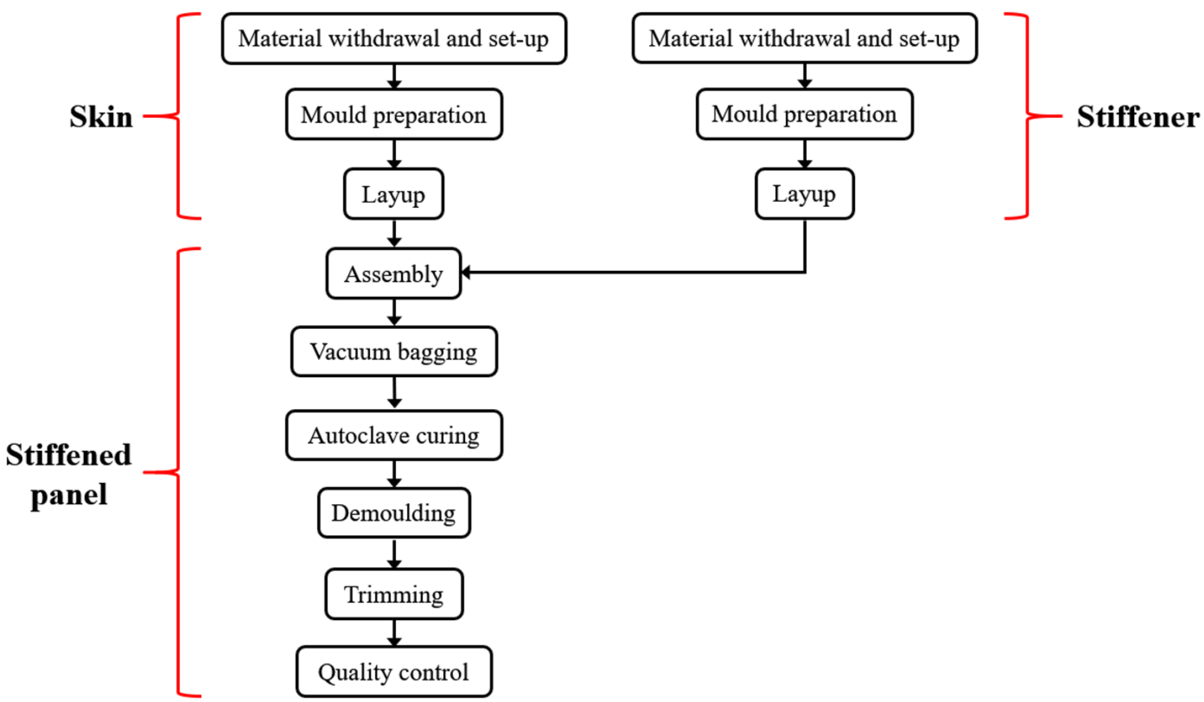

FIGURE 5: Activity Flowchart for the manufacture of the stiffened panel.

The layup of the skin and stiffener can be done by hand, known as manual layup or ML, or by use of a machine, such as an Automated Fibre Placement (AFP) machine. Manual layup involves the worker placing composite prepreg plies by hand onto the mould. As such, it is best suited for small parts and can be labour intensive for large parts. AFP automatically places prepreg tows to create the layup. The AFP machine can have a long set-up time, but can place large quantities of prepreg quickly, making it best suited for large parts such as fuselage sections and less suited for small parts. AFP can also have difficulty with layups that have complex geometry, such as the stiffener seen in this example. Therefore, Hot Drape Forming (HDF) will need to be used with AFP to correctly shape the layup of the stiffener.

Results

The results of the optimisation can be seen in Figure 6 for the case where Manual Layup (ML) is used to manufacture the stiffened panel, and the case where Automated Fibre Placement (AFP) is used.

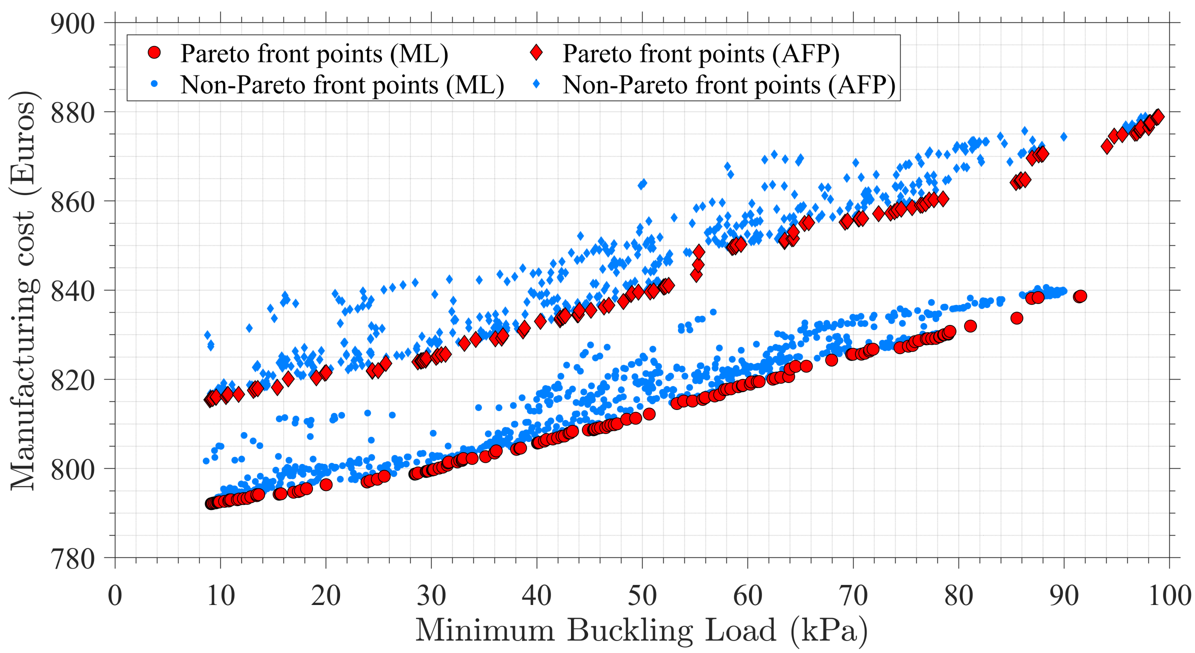

FIGURE 6: Results of the optimisation procedure.

It can be seen that the safety of the panel, represented by the minimum buckling load, can be increased significantly with only a relatively small increase in manufacturing cost. For example, in the case of AFP, the minimum buckling load can be increased from 10kPa to 100kPa for a relatively small increase in manufacturing cost of just 5% from 820 €to 880 €. It can also be seen that the manufacturing cost of the stiffened panel is slightly higher when AFP is used. This can be explained by the fact that AFP has a larger set-up cost, making it more suitable for large parts such as fuselage sections. The stiffened panel investigated in this example is a relatively small part, and so ML is more suitable, as reflected by the lower manufacturing cost achieved with ML in Figure 6.

Based on the Pareto front data seen in Figure 6, the average manufacturing cost of the panel with ML is 809.42 €while for AFP it is 843.41 €. The distribution of costs in terms of material, tool, machine, labour, and indirect costs for these two average designs can be seen in Figure 7 for ML and AFP. It can be seen from this figure that AFP has larger material costs than ML. This makes sense, since the composite prepreg tows needed for AFP are typically more expensive per kg than the composite prepreg plies needed for ML. AFP also has larger machine costs than ML, this is due to the fact that AFP requires the use of an AFP machine to lay the tows, and due to the need for a Hot Drape Forming (HDF) oven for forming the stiffener to shape. ML has higher labour costs than AFP, this make sense since because ML is a more labour-intensive process than AFP.

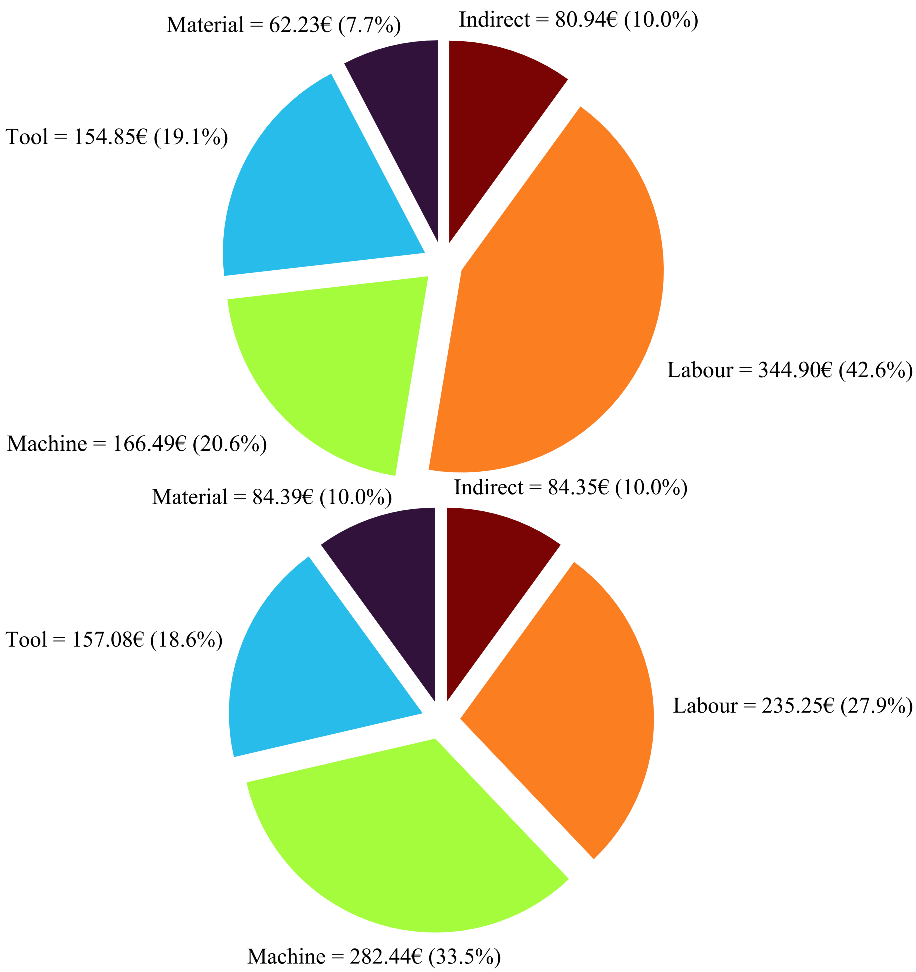

FIGURE 7: Cost type distributions for the two average designs for ML (top) and AFP (bottom).

The activity cost distributions for the two average designs can be seen in Figure 8 for ML and AFP. It can be seen that the costs of most activities are the same or very similar between ML and AFP. However, the activity Material withdrawal, inspection, and set-up, which includes prepreg costs and mould costs, is noticeably more expensive for AFP than for ML. This is because the composite prepreg tows needed for AFP are typically more expensive per kg than the composite prepreg plies needed for ML. The mould costs depend on the surface area of the part, and so they will be the same.

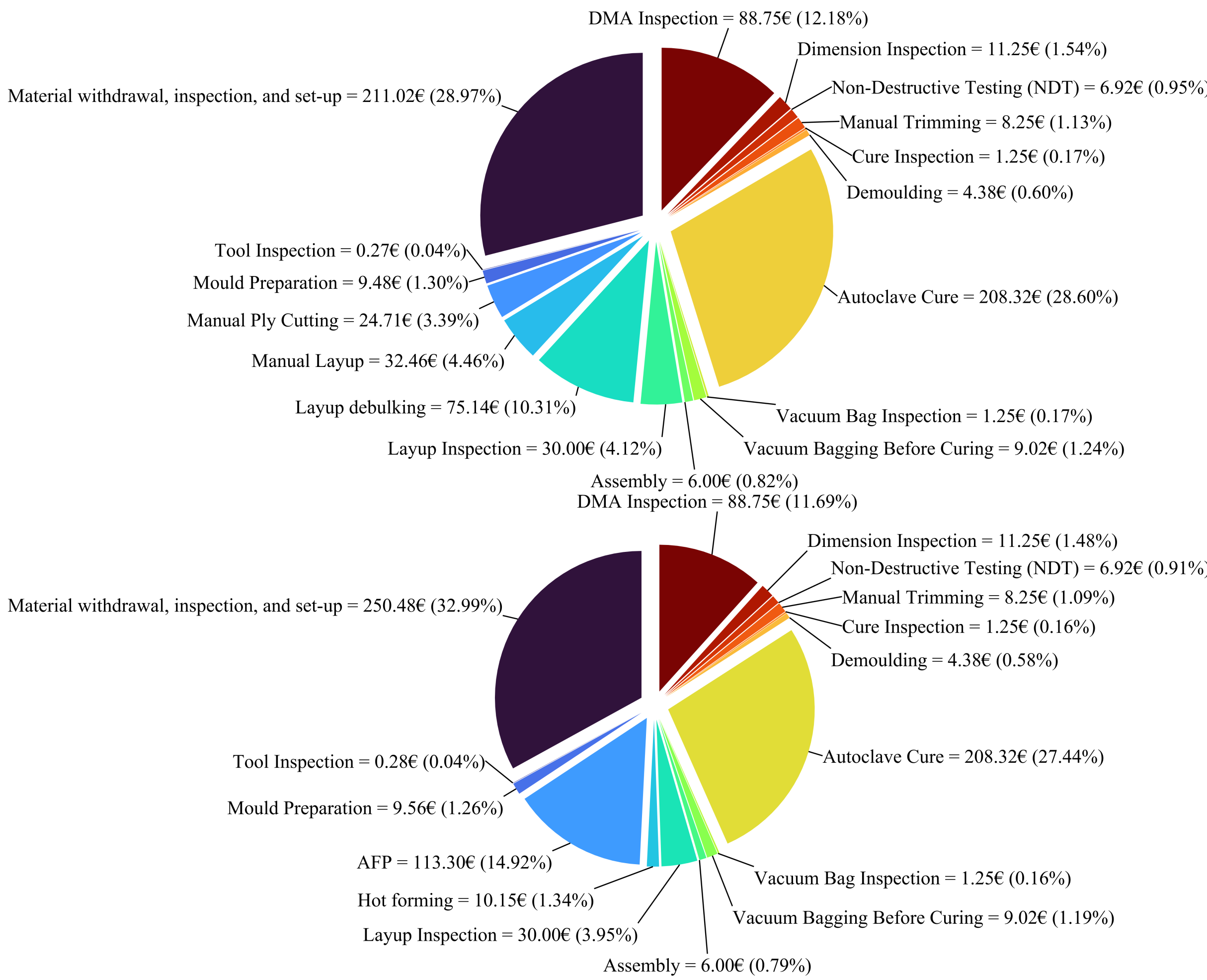

FIGURE 8: Activity cost distributions for the two average designs for ML (top) and AFP (bottom).

CONCLUSION

hThis paper presented a novel methodology for the bottom-up manufacturing cost optimisation of composite aircraft structures for Automated Fibre Placement (AFP) techniques. The proposed bottom-up approach divides the manufacturing process into many individual activities, making it applicable to a wide range of composite aircraft structures. This approach also splits the costs into material, tool, machine, labour, and indirect costs, enabling the precise cost analysis of these structures. A numerical example, featuring a mono-stiffener composite panel, was investigated. The manufacturing cost of manual layup was compared against that of automated layup using an Automated Fibre Placement (AFP) machine. Results indicate that the average cost of manual layup was 810 €, while for automated layup it was 840 €. This suggests that manual layup is superior, in terms of cost, for the manufacture of the mono-stiffener composite panel. It was also found that a significant increase in safety, represented by increase in the minimum buckling load from 10kPa to 100kPa, could be achieved with only a small increase in manufacturing costs of 5% from 820 €to 880 €.

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