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Layup time for an Automated Fibre Placement process in the framework of a detailed sizing optimisation

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ABSTRACT

Automatic Fibre Placement manufacturing processes have become the aerospace industry standard for the production of large-scale composite components. Besides the challenges linked with the manufacturing of such components, their design process is also complicated leading to the two mainly being treated as different subjects. In this work, the aspect of the layup time required to manufacture the composite component is introduced as an objective function in a detailed sizing optimisation process. The methodology presented is able to identify how the material is going to be laid on the tool, using the sizing information available via a zone-based modelling of the thickness and stiffness properties of the structure. The method is applied to the skin of an aircraft wing and a trade-off between the structural weight and layup time is observed. Results demonstrate that the bi-objective optimisation is a promising tool for reducing the structural mass, while keeping the layup time to acceptable levels by benefiting from a more detailed structural modelling.

1. Introduction

Over the last decades, Carbon Fibre Reinforced Polymer (CFRP) materials have been increasingly used in the aerospace industry due to the reduced weight and enhanced mechanical characteristics they offer. More specifically, the most recent passenger aircraft families from the two major aerospace corporations, i.e. the Airbus A350 and Boeing 787, have been manufactured using composite components which have accounted for more than 50% of their structural weight. However, composite components are also more complex and expensive to manufacture.

The manufacturing cost of a component depends on multiple factors including the type of manufacturing process employed, the material used, the geometric complexity of the parts and the assembly and labour costs. Zhao et al. [1] and Chen et al. [2] developed a method to analyse production cost which can take different manufacturing processes and materials into consideration. In the aerospace industry, Automatic Tape Laying (ATL) and Automatic Fibre Placement (AFP) have been established as the methods used to manufacture large-scale CFRP components, such as wing and fuselage skins, despite their high original acquisition cost which is offset by the increased productivity rates that can be achieved compared to manual layup.

Therefore, optimising the ATL or AFP manufacturing process to get a maximum productivity is of high importance. The broad spectrum of research work performed on automated prepreg layup has been summarised by Lukaszewicz et al. [3], Brasington et al. [4]. This study focuses on minimisation of the time spent during the machine layup. It should be mentioned that the time spent laying material is only a portion of the entire manufacturing time during the AFP process. A study from Electroimpact [5] found that only 27% of the total manufacturing time was spent during layup, which matches the 24% reported by Boeing [6]. On the contrary, the time required for inspection and repairs was measured to be higher at 32% and 63% respectively. Minimising the delays linked with inspection and repair has been more extensively researched. More specifically, the repair time can be minimised by optimising the path plan of the machine [7]. On the other hand, the inspection of the manufactured component is mainly performed manually in the aerospace industry. However, the inclusion of more non-destructive testing in the near future should

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significantly decrease the inspection time, making the layup time even more relevant for the overall reduction of the total manufacturing time.

The increase in productivity by a reduction of the layup time has been identified as an area of future research [3], which is however constrained by secondary operations, machine downtime and the design of the part. Design for manufacturing has also been listed as a research opportunity in a recent review of AFP [4]. The main challenge with design for manufacturing is the data exchange and communication between different disciplines involved in the process such as design, process planning, manufacturing and inspection [8].

Lukaszewicz et al. [3] and Lozano et al. [9] have identified the lack of research works dealing with the optimisation of the cycle time of the AFP manufacturing process in a structural design framework. Indeed, only few research works have combined structural and manufacturing considerations in an optimisation framework. Phillips and Guo [10], Phillips [11] introduced the manufacturing time and cost in a Multidisciplinary Optimisation framework using a Process Based Method which is however better suited for preliminary design stages and not a more detailed sizing stage. In the work of Hagnell and Åkermo [12], the manufacturing time is estimated using geometry complexity metrics which fail to consider manufacturing time reductions which could occur with exploration of alternative thickness and stiffness distributions in the structure. Finally, Irisarri et al. [13] explore the manufacturing complexity of a composite component in a detailed sizing optimisation process however, the procedure is tailored to a specific manufacturing method called the Quilted Stratum Process.

The aforementioned studies consider the manufacturing process time at a higher level without using information such as the detailed thickness and stiffness distribution of material across the structure. The work of Ückert et al. [14] combines structural and layup time requirements in a late design stage with finalised stacking sequences. Time savings are achieved by avoiding incomplete ply courses and adapting ply contours. However, all design modifications are performed manually and not in an automated optimisation framework. Similarly, Astwood et al. [15] study the influence of the composite design on the production speed by evaluating the ply perimeter to ply surface ratio. Different laminate designs are examined and the computed cycle times are compared against both the results from a simulation using specialised software from MAG Cincinnati manufacturer and the actual cycle times when manufacturing the coupons using the same machine. The study provides recommendations on how to improve the manufacturing time of laminates by taking into account their detailed design but is not implemented in an optimisation process.

In this study, the layup time is introduced as an objective function in the first of the two stages of a detailed sizing optimisation process. During this optimisation stage, the structural mass is also used as an objective function and the constraints considered are both structural, such as buckling and strength, but also design and manufacturing rules commonly used in the aerospace industry. The aircraft structure is modelled using a Global Finite Element Model (GFEM). In order for any sub-component of the aircraft to be sized, multiple elements are linked together to form the so called patches, representing zones of a uniform stacking sequence. The thickness and stiffness of each patch is represented by a generic stack [16].

The novelty of the work lies in the calculation and optimisation of the layup time required to manufacture the component. This is performed by treating the laminated structure as a series of shared courses of material, whose shape depends on the geometry of the structure and the fibre orientations that are to be laid during manufacturing. Each of these courses is further split up into sub-courses depending on the patch discretisation of the structure and the thickness distribution across the patches which varies between each optimisation iteration. The bi-objective optimisation has been applied to the skin of a wing and leads to a trade-off between a slight increase in structural weight for a reduction of the time required to lay down the material. Furthermore, it has been demonstrated that smaller patch sizes, which are usually avoided during the design of the aircraft because they are expected to lead to increased manufacturing complexity, should actually be preferred during the design. The reason for this is that the bi-objective optimisation can take advantage of the increased design freedom to reduce the weight while keeping the layup time similar to that of a design with larger patch sizes.

The rest of this paper is structured as follows: In Section 2, the detailed sizing optimisation process employed in this study is summarised. The formulation of the layup time as an objective function in the optimisation is formulated in Section 3. Results of a bi-objective mass and layup time optimisation are presented in Section 4 and the findings of this work are summarised in Section 5.

2. Detailed sizing process

The detailed sizing process of a composite component is a topic widely researched [17,18] and involves the determination of the stacking sequence across the span of the structure. The challenges associated with this task are mainly linked to the heavy computational tasks involved in the computation of the GFEM responses, the mixed continuous and discrete nature of the optimisation problem and the increased design freedom offered by the anisotropic nature of composite materials. Zero-order algorithms are widely accessible and can handle the discrete characteristics of the composites design problem. However, their applicability has been limited to smaller design problems [19, 20]. For the case of large scale aerospace structures, the evaluation of numerous physical constraints such as strength and stability requires the responses of the GFEM which are computationally expensive. Therefore a gradient-based optimisation algorithm must be used to reduce the number of iterations required until convergence of the design. However, gradient-based algorithms are suited for continuously formulated functions, which is not the case for constraints imposed on the laminates by design rules and manufacturing processes followed in the aerospace industry. The established way of dealing with this challenge is to split up the stacking sequence optimisation process in two stages [21–23].

In the authors' previous works a two-stage process has been developed to deal with the stacking sequence optimisation of large-scale aerospace components [16,24]. The overview of the two stage process is presented in Fig. 1. More precisely, during the first stage of the gradient-based optimisation of the structure [16], the thickness and stiffness properties of the laminates are modelled using generic stacks which will be presented in more detail in the following section. The design variables used in this optimisation problem are continuous and all constraints associated with the responses of the GFEM are formulated and considered. Naturally, the continuous result of the gradient-based optimisation does not fulfil all of the discrete requirements of a stacking sequence. These are satisfied through the discrete optimisation, during which the number of plies per patch remains constant after being rounded up to the nearest integer or even number of layers. The objective of the optimisation is to minimise the difference between the continuous and discrete stiffness. The problem is expressed as a Mixed Integer Linear Programming formulation [24]. The physical constraints of the structure are not taken into account at this stage and therefore a re-evaluation of the GFEM model must be performed once the optimum discrete stacking sequence is retrieved. In the case of physical constraint violations, the two stage optimisation process has to be repeated again using an increased design factor. The key to retrieving a discrete design which fulfils the physical requirements is to formulate as many composite design and manufacturing rules as possible in the first stage of the optimisation. The existence of these constraints bridges the information gap between the two optimisation stages even though the composite guidelines are formulated in a continuous domain in the first stage of the optimisation.

The calculation of the layup time can be performed in both the first and second stage of the optimisation. If the layup time is computed

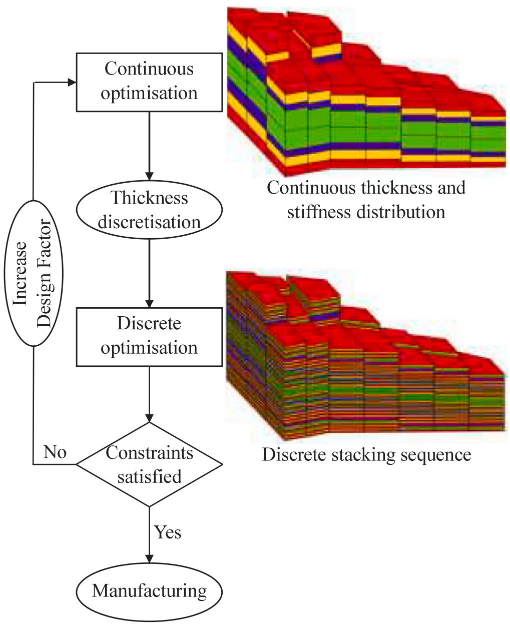


Fig. 1. Overview of the two stage detailed sizing optimisation process. The discrete stacking sequence graph has been created using the code developed in the work of Macquart [25].

in the second stage of the optimisation, the exact discrete stacking sequence of the structure is known at any point and therefore the result would be more accurate. However, during the latter optimisation stage, the design freedom is limited due to the fixed number of layers per patch. Additionally, any exploration of the design space towards a direction that undermines the optimal stiffness match, shall probably lead to violations of the physical constraints of the structure when these are re-evaluated after the discrete optimisation. Therefore, the decision to include the layup time as an objective function in the first optimisation stage has been made, as this allows a proper design exploration both in terms of stiffness and thickness distribution while all structural requirements are satisfied.

2.1. Problem formulation

The thickness and stiffness properties of the structure are modelled using generic stacks. A generic stack is comprised of multiple generic layers. The exact orientation θ_i and stacking sequence of these plies is fixed during the optimisation, whereas the individual thickness t_i of each generic ply corresponds to a design variable which can take any real positive value. In a very simple case, a generic stack can be comprised of 8 generic plies as shown in Fig. 1. In reality, the number and stacking sequence of the generic stack needs to be chosen so that the resulting thickness and stiffness does not depend on the modelling decisions [16].

The optimisation algorithm used is NLPQLP [26,27], a sequential quadratic programming algorithm which is available in the Airbus in-house Multidisciplinary Design and Optimisation platform called *LAGRANGE* [28]. It is worth noting that the optimal stacking sequence attributes are not limited to solely being a function of the structural weight or the CFRP layup time, but can also take into account performance related metrics such as the Breguet range. In this work the two objective functions are the structural weight and layup time. The mathematical formulation of the problem is:

$$\begin{aligned} \text{minimise} \quad & w_1 M(t) + w_2 T(t) \\ \text{subject to} \quad & g_k(t) \geq 0 \quad k \in \{1, \dots, K\} \end{aligned} \tag{1}$$

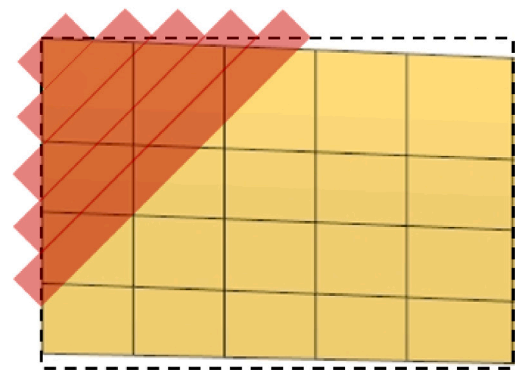


Fig. 2. Illustration of the geometry of 45 degree courses computed for part of a component.

where w_1 and w_2 are weight factors applied to the two objective functions of structural mass $M(t)$ and layup time $T(t)$. Both objectives are a function of the thicknesses t of the generic layers. The objective function of the structural mass is expressed as:

$$M\left(t_{ij}\right) = \sum_{j=1}^{J} \sum_{i=1}^{I} t_{ij} A_j \rho \tag{2}$$

where i indicates the position of a generic layer in the generic stack of patch number j. Additionally, A_j is the area of the surface of each patch and ρ is the density of the material used to manufacture the component of interest. The formulation of the layup time required for the AFP process is presented in detail in the following section. Finally, $g_k(t)$ are the K constraints applied to the optimisation problem. The physical constraints used in this study are strength and buckling, while the design and manufacturing rules used are blending, minimum percentage and maximum dropping. Additionally symmetry, balance and two external covering plies of 45°/−45° are enforced by design variable linking or by altering the design variable gauges. For more information on the formulation of the constraints applied in the gradient-based optimisation, the reader is invited to further reading on previous work by the authors [16].

3. Layup time calculation

In this section, the methodology derived to model the AFP process using the amount of information available inside the gradient-based optimisation is demonstrated. The varying stiffness of the structure across its span is modelled by using multiple constant stiffness zones or patches. Each of these patches is modelled using a generic stack and therefore a continuous stacking sequence is known, which however is not compliant with discrete design and manufacturing criteria. Previous works [29,30] have expressed the layup time required to manufacture one single rectangular ply of CFRP material using an ATL process. The layup time depends on the dimensions of the ply, the width and number of pre-impregnated uni-directional CFRP material strips or tows that the machine head can lay in parallel, the orientation at which the material is laid and several parameters related to the speed, acceleration and delays of the machine. However, when considering large-scale aerospace components, examining the layup time of each single ply in a patch is not reasonable, since all of the patches share plies which will be manufactured in one go and not individually. Therefore, it is sensible to study the layup time for the component of interest as a collection of material courses as demonstrated in Fig. 2. The AFP machine manufactures each course by combining multiple tows to be laid simultaneously.

A different set of material courses spanning the component has to be computed for each different fibre orientation that is expected to be manufactured. The layup time required to manufacture one single course [30] is expressed as:

$$T_{course} = l_{course}/v_0 + v_0/2\left(1/a_{acc} + 1/a_{dec}\right) + T_{delays/course} \tag{3}$$

where l_{course} represents the length of the course, v_0 the maximum layup speed achieved by the machine, a_{acc} and a_{dec} the acceleration and deceleration of the machine head respectively and $T_{delays/course}$ additional delays associated with each course.

At this point, the assumptions made in order to compute the layup time of AFP manufacturing process, in the framework of the detailed sizing optimisation, have to be listed. An exact computation of the layup time can be preformed using dedicated software provided by the manufacturers of AFP machines or by CAD software able to perform path planning processes [31]. Path planning is a widely researched topic [7] which in itself can be an area with many challenges regarding the structural defects arising, especially when working with curved fibre paths.

A first assumption made during the sizing optimisation performed in this work is that straight fibre paths are employed to manufacture the component. Although optimisation of fibre steered CFRP is an actively studied topic [18], the standard in the aerospace industry, both in terms of design and manufacturing, has been constant stiffness laminates. What is more, the developed methodology assumes that the orientation at which fibres are placed and the ply shares for these orientations can be computed during the optimisation. To the best of the authors' knowledge, this cannot be performed inside gradient-based algorithms dealing with fibre steered CFRP, since these are normally modelled with lamination or polar parameters and require a separate optimisation stage to extract all this detailed information.

Besides treating only straight fibre paths of specific orientations, these orientations are also considered to be invariant, regardless of geometric complexities, such as doubly curved surfaces, which inevitably alter the true fibre orientation. Additionally, the methodology that will be further developed in this work is limited to relatively flat or small curvature paths. For more complex geometries or cylindrical components the v_0 maximum layup speed is not achievable and would have to be decreased across the length of the course.

Furthermore, the starting point for the first course of a given fibre orientation is chosen at a random corner position of the component. Even though the starting point may influence the quality of the manufactured part, especially when dealing with fibre steering [32], the effect should have less impact for constant stiffness laminates particularly due to the staggering of plies. Staggering refers to the shifting of the courses in the ply with respect to the courses in an identical ply laid previously, in order to spread out and minimise the structural impact of course overlaps and ply drops [33,34]. The number of courses considered for each fibre orientation depends on the geometry of the component, the fibre orientation, the width of the course which will be used during manufacturing w_{course} and the overlap between courses placed adjacent $d_{overlap}$.

Finally, the order of the generic plies is not accounted for during the computation of the layup times. Instead, the continuous thicknesses of all generic layers with the same orientation within a patch are summed up to a total thickness per orientation and patch. This also means that any delays associated with re-positioning the machine from one location of the part to another one are not accounted for, since the exact stacking sequence during the first stage of the optimisation is unknown.

The mid-line of each course traverses through a set of patches. The order of the patches in this set and their corresponding lengths can be pre-calculated before the optimisation and remain constant throughout. For any course, a set of patches $\mathbf{J}$ is calculated with $\mathbf{J} = \{j_1, \dots, j_n\}$. The course will only be manufactured if all patches $j \in \{j_1, \dots, j_n\}$ share a common thickness. As mentioned previously, the thicknesses of all generic layers within a patch are summed up for each fibre orientation available in the set of manufactured fibre orientations $\mathbf{\Phi}$. Therefore,

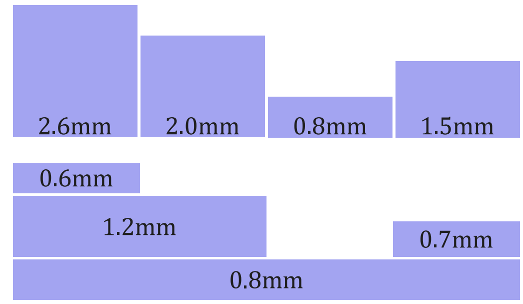


Fig. 3. Schematic representation of the layup strategy used to manufacture the thickness profile of 4 patches. The indicated thicknesses refer to the same fibre orientation.

the cumulative thickness of each fibre orientation for each patch can be expressed as:

$$s_{j\theta} = \sum_{i=1}^{I} t_{ij} \quad \forall i, j \quad \theta_{ij} = \phi \in \mathbf{\Phi} \tag{4}$$

where θ_{ij} is the fibre orientation of a specific generic ply.

In the case that all patches belonging to a course do not share the same thickness, then multiple combinations of sub-courses arise. These combinations depend on the exact thickness distribution amongst the patches, which changes throughout the course of the optimisation. A visual example of this logic applied to a specific thickness distribution across 4 patches is given in Fig. 3. The way such a material distribution would be manufactured is that the minimum shared thickness of 0.8 mm would be laid across all patches, followed by 1.2 and 0.7 mm of thickness spanning across the first two and the last patch respectively. Finally, the remaining material of 0.6 mm thickness would be placed.

For a course spanning the ordered set of patches $\mathbf{J}$, where $n(\mathbf{J})$ is the number of patches in this set, the total number of different sub-course combinations that might arise is $N = \sum_{l=1}^{n(\mathbf{J})} l$, where index l indicates a group of sub-courses which span through $n(\mathbf{J}) + 1 - l$ patches, marked with red rectangular boxes in Fig. 4. Each group of sub-courses contains $k = l$ sub-courses. For example, the first group contains one sub-course which includes all patches that the mid-line of the course traverses through. The last group of sub-courses contains $k = n(\mathbf{J})$ potential sub-courses with each of them being comprised only one individual patch. As expected, only a few of all the different sub-course combinations can exist for any given thickness distribution. This depends on whether the minimum thickness that these patches share is 0 or not. For a given ordered set of patches, the minimum thickness for any fibre orientation θ is calculated as:

$$m_{lk\theta} = \min\left(s^*_{jl\theta}\right) \quad \forall l \in [1, n(\mathbf{J})], k \in [1, l], j \in \mathbf{J} \tag{5}$$

In the equation above, $s^*_{jl\theta}$ are the modified thicknesses for the different sub-courses and are computed as:

$$s^*_{jl\theta} = \begin{cases} s_{j\theta} & \forall j \in \mathbf{J}, l = k = 1 \\ s_{j\theta} - \sum_{\lambda=1}^{l-1}\sum_{k=1}^{\lambda} c_{j\lambda k} m_{\lambda k\theta} & \forall l \in [2, n(\mathbf{J})], k \in [1, l], j \in \mathbf{J}. \end{cases} \tag{6}$$

For the first group of sub-courses ($l = k = 1$), the modified thickness $s^*_{jl\theta}$ is equal to the cumulative thickness for each fibre orientation ($s_{j\theta}$) as computed during the optimisation. For all subsequent groups, the modified thickness has to be adjusted to account for material that has already been accounted for in previous groups and sub-courses. In Eq. (6) $c_{j\lambda k}$ is a coefficient calculated as:

$$c_{j\lambda k} = \begin{cases} 1 & \forall \quad j \in [k, k + n(\mathbf{J}) - \lambda] \\ 0 & \forall \quad j \notin [k, k + n(\mathbf{J}) - \lambda] \end{cases} \tag{7}$$

The layup time for all the sub-courses within a course can then be calculated by slightly modifying Eq. (3) to:

$$T_{course} = \sum_{l=1}^{n(\mathbf{J})}\sum_{k=1}^{l} m_{lk\theta}/t_{tow}\left(l_{lk}/v_0 + v_0/2\left(1/a_{acc} + 1/a_{dec}\right) + T_{delays/sub-course}\right).$$

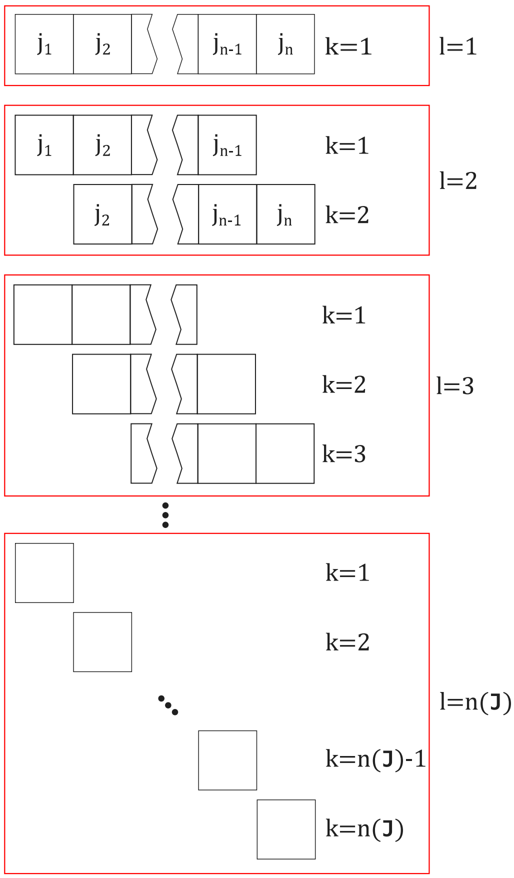


Fig. 4. Overview of all potential sub-courses that might rise for any random thickness distribution, for a material course spanning across n patches. Each black square represents a patch.

(8)

In the above equation, t_{tow} is the thickness of the tow that will be used during manufacturing and therefore the ratio $m_{lk\theta}/t_{tow}$ denotes a continuous number of plies. The length of each sub-course l_{lk} can easily be calculated since the corresponding length of each patch l_j in the course is known:

$$l_{lk} = \sum_{j=k}^{k+n(\mathbf{J})-l} l_j. \tag{9}$$

For patches along the outer edges of the component, an 100% boundary coverage is assumed for the calculation of the corresponding lengths l_j.

The delays $T_{delays/sub-course}$ considered for each sub-course manufactured, are limited to the time required to cut the ply and move the head of the machine downwards and upwards. The total layup time T for the entire component is calculated by summing all the lay-up times for each course and fibre direction

$$T = \sum_{\theta} \sum_{courses} T_{course}. \tag{10}$$

Details on the computation of the derivative for the layup time objective function are provided in Appendix.

It should be noted that the methodology presented above is not limited to a modelling of the structure using generic stacks. Lamination parameters [35], which have been extensively used to model the structural properties in a similar two-stage optimisation process [22], can also be employed in specific use cases. If for example the fibre orientations used are $\{0, 90, 45, -45\}$, then the number of layers for each of these orientations can be easily calculated during the optimisation

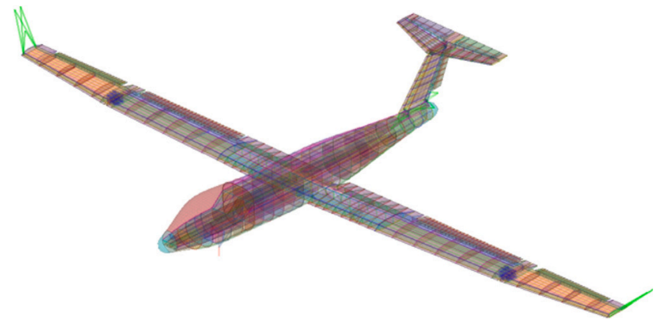


Fig. 5. GFEM model of OptiMALE, the industrial demonstrator used in this work.

using a system of linear equations, when knowing the total thickness of the laminate and the lamination parameters corresponding to the flexural stiffness matrix **A**. Finally, it should be mentioned that the presented mathematical formulation of the layup time as an objective function can also be used as a constraint in the optimisation problem with very minor modifications.

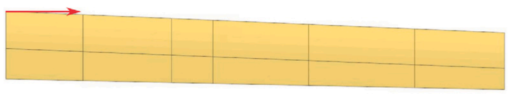
4. Results

The developed methodology is applied to the wing skin of an industrial demonstrator. It is shown that there is a trade-off between the layup time required to manufacture the component and its structural weight.

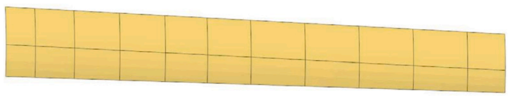
4.1. Model description

The industrial demonstrator used in this work is OptiMALE [36], a Medium Altitude Long Endurance unmanned aircraft presented in Fig. 5. The aircraft is modelled using a coarse GFEM model consisting of 1D and 2D structural elements. The model is subjected to 19 static load cases, which have been pre-selected from a complete flight envelope, covering different operating altitudes, Mach numbers and load factors. The outer part of the wing of the aircraft is detachable due to storage and transportation requirements which leads to a total of 4 sub-components, 2 for each of the upper and lower parts of the wing skin. The bi-objective optimisation is only applied to one component in the structure, more specifically, the upper, inner part of the wing skin. Only this part of the structure is sized during the optimisation while the other sub-structures in the wing i.e. remaining wing skins, spars, stringers and ribs, are sized based on a previously performed, single objective weight minimisation. This is done in order to eliminate all influences to the structural mass of the wing skin which would be stemming from load redistribution across the other sub-components on the wing and only focus on the effect the layup time has on the sizing and therefore mass of the skin. Buckling constraints are applied to the skin of the wing and the assumption that each buckling field is simply supported, subjected to in-plane loads and specially orthotropic is made. Concerning strength constraints, the maximum strain criterion is applied to the skin of the wing. In terms of composite design constraints, symmetric and balanced laminates are enforced via design variable linking. Blending constraints, also commonly referred to as continuity constraints, are applied between all adjacent patches in the structure to ensure manufacturability and integrity of the laminated composite. Finally, constraints that limit the minimum and maximum ply share are applied for each fibre orientation used.

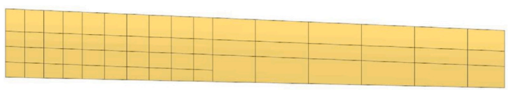
Regarding the discretisation of the structure into patches, three schemes of different coarseness are examined in this study. The 12, 22 and 58 patches are shown in Figs. 6(a)–6(c) respectively, for the inner part of the suction side of the wing, which has rough dimensions of 10 and 1.3 meters in the span and chord direction respectively. Concerning



(a) Patch discretisation #1



(b) Patch discretisation #2



(c) Patch discretisation #3

Fig. 6. Three patch discretisations of different coarseness have been applied to model the inner part of the suction side of the skin of the wing. The orientation of the zero degree fibres is indicated by the red arrow in patch discretisation #1 and is at a slight angle with respect to the backwards swept wing. The rest of the fibre orientations are defined relatively to the zero degree orientation.

Table 1
Performance data for a typical AFP machine. Data partly extracted from Haffner [30] and approximated from Airbus proprietary documents.

Parameter	Value
v_0	1.4 m/s
a_{acc}	0.76 m/s^2
a_{dec}	0.76 m/s^2
$T_{delays/sub-course}$	3 s
t_{tow}	0.184 mm
w_{course}	150 mm
$d_{overlap}$	5 mm

Table 2
Weight factors used in the two objective functions to derive the design points of patch discretisation #1. The design points corresponding to the weight factors are in order of descending layup time.

w_1	100	100	100	100	100	100
w_1	10^{-6}	10^{-4}	2×10^{-4}	8×10^{-4}	10^{-3}	5×10^{-3}

the number of generic layers used to model the stiffness properties of the structure, a maximum of 32 generic layers resulting in 12 design variables, due to symmetry and balance requirements, have been used for the thickest regions of the wing covers. For the thinnest, outer parts of the wing, 8 generic layers leading to 3 design variables for each patch have been chosen to model the properties of the structure. More details on the structural model and the optimisation model setup can be found in previous work by the authors [37].

4.2. Bi-objective optimisation

The bi-objective sizing optimisation is performed for all three patch discretisations shown in Fig. 6. By altering the ratio between the weight factors used for each objective function in Eq. (1), a trade-off between the structural mass and the layup time is observed. This trade-off is visualised for the three patch discretisations in the Pareto front of Fig. 7. A Pareto front includes all non-dominated optimisation solutions, meaning that none of the objectives can be further reduced without increasing the other one. The AFP machine parameters that have been applied to the case study are summarised in Table 1. The weight factors used for each objective function when deriving the design points of patch discretisation #1 are summarised in Table 2. As the weight factor of the layup time increases, the algorithm converges to design points with a lower layup time. It should be noted that the optimisation algorithm handles the entire mass of the aircraft in tonnes and the layup time in seconds. The reason behind choosing the specific order of magnitude for the weight factor of the structural mass is because it also influences the aggressiveness of the convergence hence reducing the chances of the optimiser getting trapped in a local minimum.

As expected, the minimum structural mass corresponds to the highest layup time, which also implies the highest manufacturing complexity. On the contrary, as the layup time decreases, the structural mass of the wing increases. This trade-off can be explained when looking in more detail at the thickness distribution across the patches. In Fig. 8(a) the total thickness of each patch is shown for design *Points 1* and *2* for patch discretisation #1. The thickness is plotted in blue and red for each design point respectively. First of all, it can be seen that the reduced structural mass of design *Point 1* does not correspond to a decreased thickness in all patches. Instead, the patches towards the leading edge are thicker in design *Point 1* when compared to *Point 2*, while the opposite is true for the patches closer to the trailing edge. Therefore, the design points resulting from the bi-objective optimisation in this case differ quite significantly in terms of thickness distribution.

The resulting thickness and stiffness properties of any design depend on multiple contradicting requirements coming both from the constraints but also the objective function of the optimisation. In Fig. 8(b), the effect that the layup time objective function has on the thickness distribution of 45 degree plies can be seen. In this case, 0 degree fibres would be manufactured along the span of the wing. Therefore, when manufactured, 45 degree courses of material can traverse across patches neighbouring in the span direction, patches neighbouring in the chord direction, a combination of the two and finally patches placed diagonally and therefore not directly neighbouring. In design *Point 2*, which is plotted in red, it can be seen that the need to reduce the layup time has resulted in a smoothing of the thickness in patch groups “a”, “b”, “c” and “d” as seen in Fig. 8(b). Therefore, one of the ways the optimiser is reducing the layup time is by minimising the number of ply cuts which are linked with the delays mentioned in Eq. (3). Of course, the minimisation of the layup time inside the optimisation framework depends on multiple other contradicting factors. For example, if minimising the ply drops between neighbouring patches for certain fibre orientations is advantageous for the reduction of the layup time, then this alters the optimal thickness and stiffness distribution of a minimal structural mass design. Any increase in mass is also unfavourable for the layup time of the laminated structure since more material must be deposited by the AFP machine. Finally, it is worth mentioning that different thickness profiles across the wing can also influence the complexity of support structures such as the stringers. This impact is beyond the scope of the study but should be taken into consideration when examining the manufacturing time of an entire wing.

Further observations can be made when comparing the Pareto fronts for the different patch discretisations. First of all, the finer patch discretisation obviously leads to a design with a lower mass, as seen by the difference between *Points 1, 3* and *6*. The design of *Point 6* is also linked with an even higher layup time. As the structural design freedom provided to the optimiser is increased by including more patches, the thickness and stiffness can be tailored to locally meet strength and stability requirements, without overdimensioning larger areas of the skin. This leads to more thickness differences between neighbouring patches which in turn implies the usage of more sub-courses of material. As mentioned earlier, since each sub-course is linked with its own time delays related to cutting the course and moving the head of the machine up and down, the overall layup time increases.

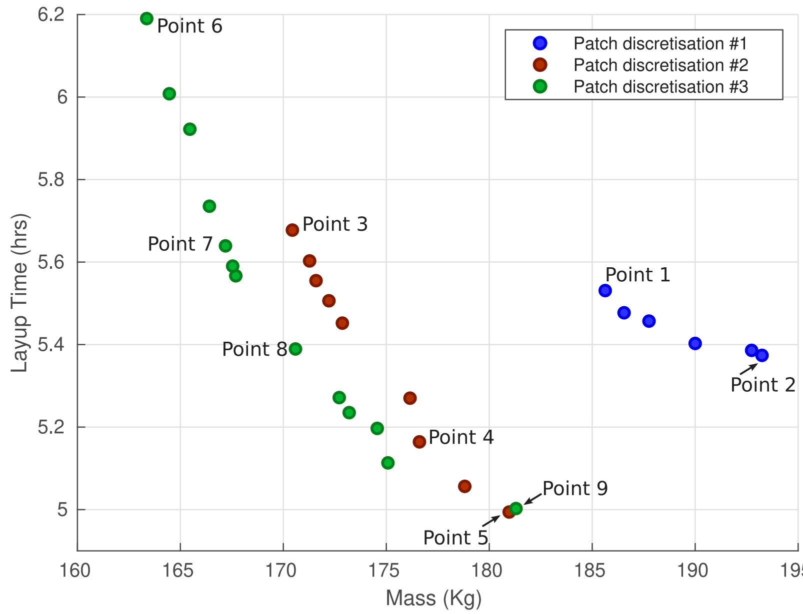
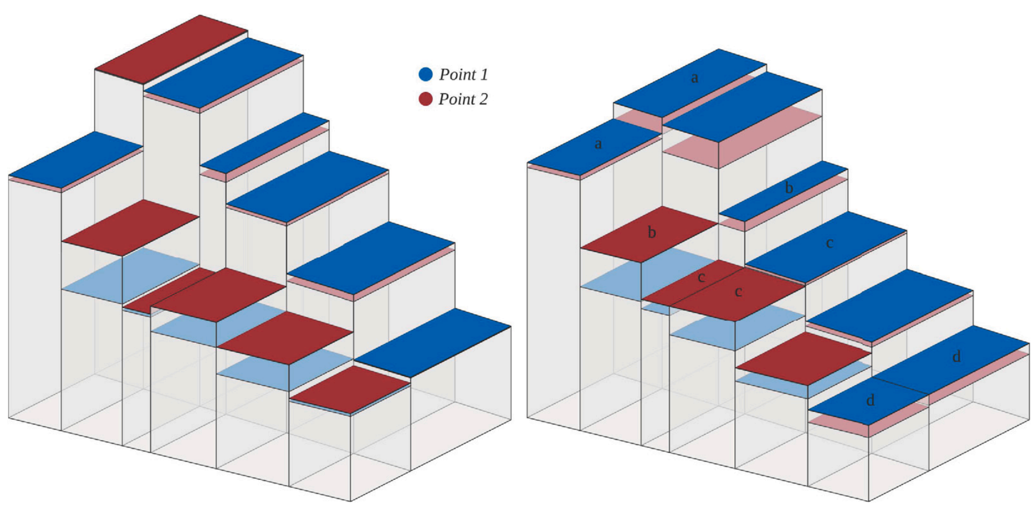


Fig. 7. Pareto front distribution of the solution of the bi-objective optimisation applied to the three different patch discretisations.



(a) Total thickness of each patch.

(b) Total thickness of the 45 degree generic layers in each patch.

Fig. 8. Thickness distribution across patch discretisation #1 for design *Points 1* and *2* of Fig. 7. Blue and red indicate the thickness distribution of design *Points 1* and *2* respectively. The orientation of the patches is the same as the one shown in Fig. 6, meaning that the top left patch is on the leading edge of the wing root. The thicknesses between Figs. 8(a) and 8(b) are not in scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

What is also worth mentioning is that the Pareto fronts for patch discretisations #2 and #3 appear to roughly coincide towards the design area of a minimum layup time as seen by *Point 5* and *Point 9*. This is reasonable due to the fact that these designs are driven by a smoothing out of thickness differences across patches to allow for the manufacturing of longer courses of material. The design freedom to perform such changes is achievable by both discretisations #2 and #3. In the case of patch discretisation #1, the design corresponding to the minimum layup time corresponds to a higher structural mass compared to the equivalent designs of the other two discretisations. This occurs because the coarseness of discretisation #1 drastically limits the design freedom causing overdimensioning of the structure. This highlights the point that the layup time is not only driven by the number of ply cuts but also on the volume of material being laid.

On the matter of choosing a suitable design point from the Pareto front, one question that rises is whether a design with a higher mass and lower layup time will be preferred by the relevant aircraft design team. For example switching from *Point 3* to *Point 4* in the Pareto front of Fig. 7 increases the mass of the wing skin by approximately 6 kg (3.6%), while reducing the layup time by around 30 min (−9%). This decision may be justified for aircraft projects with a high production rate such as single aisle aircraft families.

Even if a design team is not willing to increase the structural mass in order to reduce the layup time, the bi-objective optimisation can still be a powerful tool. The discretisation of the structure into patches is performed manually, with structural sub-components such as ribs, spars and stringers acting as the boundaries when defining these constant stiffness zones. A coarser patch discretisation may be chosen over a finer one, because the latter is associated with a higher manufacturing complexity. This is true, since, if the only goal of the optimisation is to reduce the weight of the structure, then the layup time will increase as seen by the difference in design *Points 3* and *6*.

Table 3
Mass and layup time comparison between the first and second stage of the optimisation for three selected design points. The layup time of the designs resulting from the second stage of the optimisation has been computed using the first stage of the optimisation and therefore follows the same assumptions.

Design point	First optimisation stage		Second optimisation stage	
	Mass (kg)	Layup time (hrs)	Mass (kg)	Layup time (hrs)
3	170.4	5.68	171.8 (+0.8%)	5.75 (+1.2%)
4	176.6	5.16	177.9 (+0.7%)	5.22 (+1.2%)
5	181.0	4.99	182.5 (+0.8%)	5.07 (+1.6%)

However, when introducing the layup time as an objective, the designer can still benefit from the increased design freedom by choosing a different point from the Pareto front. For example, if design *Point 7* is chosen then the mass is reduced by more than 3 kg while the layup time stays roughly the same when compared to that of design *Point 3* of the coarser patch discretisation #2. Alternatively, a reduction of approximately 30 min in layup time can be achieved for a similar structural mass if design *Point 8* is used instead of *Point 3*. Therefore, the bi-objective optimisation can assist with the reduction of weight while keeping the layup time to acceptable levels, by making use of an increased design space which would not be achievable by a single objective optimisation.

On a final note, the influence that the second stage of the optimisation has on the computed layup time is demonstrated for design *Points 3*, *4* and *5*. The total continuous thickness of each patch resulting from the first stage of the optimisation is rounded up to the nearest integer number of plies and this thickness distribution remains fixed during the second stage of the optimisation. Since the objective function of the second stage is to minimise the absolute difference between the continuous and discrete stiffness characteristics, the ply shares, which correspond to the flexural stiffness of the patch are also well maintained. As seen in Table 3, the layup time is only slightly increased for each design point. This difference is mainly due to the total thickness being rounded up, as seen by the increase in the total weight, which inevitably increases the layup time. The assumption that the thickness of each fibre orientation is treated as a single layer, which is performed during the calculation of the layup time, neglects any impact that the actual stacking sequence has on the layup time of the component.

5. Conclusions

In this work, the CFRP layup time of an AFP manufacturing process is included as an objective function in a detailed design optimisation suited for large-scale aerospace components. The sizing process is comprised of two stages, the first one being a gradient-based thickness and stiffness optimisation dealing with all constraints linked to the response of a GFEM model and the latter targeting the retrieval of discrete laminated components satisfying multiple design and manufacturing criteria. The calculation of the layup time objective is introduced in the first stage of the optimisation. Even though the information available on the stacking sequence of the component are less exact at this point, there is enough design freedom to achieve meaningful trade-offs between the two objectives.

The developed methodology is applied to an industrial demonstrator. Different weight functions are applied to each objective function in order to acquire a Pareto front of different design points. The design with the lowest structural mass is also linked with the highest layup time and vice versa. More importantly, it is shown that the bi-objective optimisation can be used to bypass coarser patch discretisations, usually applied during the design process to avoid designs with a high manufacturing complexity. A greater design freedom is linked with more manufacturing complexities and a larger layup time. This is true for an optimisation in which the minimisation of the structural mass is the sole requirement. However, the second objective function can be employed to keep the layup time to an acceptable limit while benefiting from reduced structural weight due to the increased design freedom. Alternatively, the layup time can also be implemented as a constraint in the optimisation framework to achieve the same result. Finally, instead of reducing the structural mass, it can be kept to satisfactory margins while the layup time is reduced by means of the bi-objective optimisation.

Future work can study the influence of the assumptions used in the formulation of the layup time objective function. This can be achieved by retrieving discrete stacking sequences for distinct design points of the Pareto front and then creating a detailed AFP machine plan for the manufacturing of these designs. The layup times estimated during the continuous optimisation process can then be compared against the more accurate computations for the discrete designs for the different design points.

CRediT authorship contribution statement

G. Ntourmas: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **F. Glock:** Conceptualization, Software, Supervision, Writing – review & editing. **F. Daoud:** Conceptualization, Supervision. **G. Schuhmacher:** Conceptualization, Supervision. **D. Chronopoulos:** Supervision, Writing – review & editing, Funding acquisition. **E. Özcan:** Supervision, Writing – review & editing. **J. Ninić:** Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Layup time derivative

The layup time objective function is implemented in a gradient-based optimisation framework. The derivatives for all constraints and objective functions in the framework of the Multidisciplinary Design and Optimisation platform *LAGRANGE* are all computed analytically. The formulation of the total layup time for a component as shown in Eq. (10) involves multiple evaluations of the minimum of a given set of thicknesses as seen in Eq. (5). Assuming three thicknesses t_1, t_2 and t_3, the minimum of them can be mathematically formulated both exactly as:

$$\begin{aligned}\min\left(t_1,t_2,t_3\right) = \frac{t_1}{2}\left(\frac{|t_3-t_1|+|t_1-t_2|}{|t_1-t_2|+|t_2-t_3|+|t_3-t_1|}\right)+\\ \frac{t_2}{2}\left(\frac{|t_1-t_2|+|t_2-t_3|}{|t_1-t_2|+|t_2-t_3|+|t_3-t_1|}\right)+\\ \frac{t_3}{2}\left(\frac{|t_2-t_3|+|t_3-t_1|}{|t_1-t_2|+|t_2-t_3|+|t_3-t_1|}\right)-\\ \frac{|t_1-t_2|+|t_2-t_3|+|t_3-t_1|}{4}\end{aligned} \tag{A.1}$$

and inexactly as:

$$\min\left(t_1,t_2,t_3\right) = \lim_{k\to-\infty}\sqrt[k]{{t_1}^k+{t_2}^k+{t_3}^k}. \tag{A.2}$$

The issue with the exact calculation is that the absolute values introduce a lot of discontinuities in the derivative. Additionally, the computation becomes increasingly complicated as the number of thicknesses for which the minimum has to be computed for increases. On the other hand, the accuracy of the inexact formulation becomes problematic for thicknesses with a very small relative difference and exponents $k < -100$ resulted to numerical issues in the computation of the derivative value. Therefore, all minimum values are calculated using the respective function of the programming language and the computation of the derivative is performed numerically using finite differences. This does not hinder the computational performance of the optimisation process since the layup time is only a function of the thicknesses and is not linked with the response of the GFEM model as is the case for the structural constraints in the optimisation.

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