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Cost/weight optimization of composite prepreg structures for best draping strategy

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The application of hand-laid carbon fiber prepreg is very expensive from a labor perspective. Therefore the manufacturing cost should be included in the design process. In this work, we propose a novel optimization framework which contains a draping simulation in combination with a detailed cost estimation package and the calculation of the structural performance based on FE. We suggest applying the methodology in two steps. First, a draping knowledge database is generated in which combinations of seed points and reference angles are evaluated in terms of fiber angle deviation, scrap, ultrasonic cuts and material shear. Second, a cost/weight optimization framework picks the best sets of plies during the subsequent optimization. The methodology is tested by means of a curved C-spar which is designed using plain weave and unidirectional prepreg. Different objectives in the generation of the draping database lead to different design solutions.

Keywords: Cost/Weight Optimization, Finite element analysis, Prepreg, Lay-up (manual/automated)

1 Introduction

Aircraft manufacturers aim to design airliners with the lowest possible direct operating cost (DOC). This direct operating cost includes cost for depreciation, insurance, landing fees and not least fuel consumption. As the latter is a substantial part of the DOC (20-40%, depending on the operator), one can understand why a lot of efforts have been undertaken to lower the fuel consumption. One possible strategy to save fuel is to lower the structural weight.

During the last 20 years, carbon fiber reinforced plastics (CFRP) were carefully introduced into primary aircraft structures in order to lower the structural weight. The drawback of CFRP, however, is the increased manufacturing cost. Gutowski et al. described the composite's disadvantages in terms of cost already back in 1991 [1]. In particular, the authors spotted the high labor cost as the largest single contributor to direct cost – in spite of the higher material cost.

Some years later, Rais-Rohani et al. identified the risk that the high material, fabrication and tooling costs may make the use of high-performance materials cost-ineffective. As a consequence, the costs of raw materials, tooling, fabrication, assembly, scrap, repair, certification and environmental factors should be included in the design of composite structures [2].

Since that time, a lot of research and development has been performed in the field of composite structures. For example, new material systems evolved, and automatic tape laying or fiber placement machines were installed. A lot of parts, however, were still manufactured with rather expensive hand-laid carbon epoxy prepreg systems which were cured in an autoclave. In addition, the stacking sequences generally remained the same, using a quasi-isotropic layup with 0, 90 and $\pm 45^\circ$ angles. Soutis pointed out that early composite designs were "replicas of those that employed metallic materials", and that "the high material cost and man-hour-intensive laminate production jeopardized their acceptance" [3].

Authors saw the lack of sophisticated cost models as the reason behind the absence of cost optimization frameworks for composite components, see Sobieszczanski-Sobieski and Haftka [4]. Some costing information was integrated into the design process by Geiger et al., though [5]. There, the authors presented a conceptual model for an automated design-to-cost approach by providing a framework for the decision-making process. Heinmuller and Dilts adapted this framework to the aerospace industry [6], and Kassapoglou published a series of articles on combined cost/weight optimization of aircraft structures [7–9].

Not an optimization per se, but a methodology to compare different material systems on the basis of cost/performance efficiency was proposed by Bader [10]. Among else, he mentioned the high amount of waste when cutting plies from standard prepreg. Park et al. pursued the optimization of components manufactured by resin-transfer-molding. In particular, the stacking sequence of a composite plate was optimized in order to maximize the stiffness while minimizing the mold filling time [11].

Curran et al. combined the manufacturing cost and the weight and used a simplified form of the above-mentioned direct operating cost as the objective function [12,13]. A similar approach of weighted sums was implemented in the work of Iqbal et al. who applied it on the optimization of a truss structure [14]. The work of these authors was resumed by Kaufmann et al. who used the *DOC* of composite components in combination with FE, a feature-based parametric manufacturing cost model [15] and a non-destructive testing cost model [16]. This framework incorporated the manufacturing cost of a component and the influence of its weight into one objective function.

Figure 1: Parameter adjustments can lead to a better solution DOC^* , while constant manufacturing parameters converge to DOC° . Note that this is only a schematic drawing.

In Kaufmann et al. [17], the use of a knowledge database for the sub-optimization of manufacturing cost was explored. A center wing box rear spar was optimized in terms of cost and weight. It could be shown that the initial settings of the manufacturing cost model should *not* remain constant during the optimization of the geometry of spar and stiffeners. Hence, a framework was proposed in which the machining cost of the aluminum stiffeners was sub-optimized in each iteration of the superordinate shape optimization. This idea is illustrated in Figure 1. There, it is shown that the global optimum DOC^* cannot be reached when the process parameters are not adjusted. Instead, the optimization with constant machining parameters (such as cutter diameter or cutter material) would lead to a local optimum DOC° .

In all the work performed by Kaufmann et al., only nominal fiber angles with 0, 90 and $\pm 45^\circ$ were used. In reality, particularly when manufacturing double-curved components, the manufactured fiber angles cannot match these nominal fiber angles in every point of the component due to the limitations in material shear. For the optimization of composite structures, it would therefore be advantageous to use the draping-corrected fiber angles. As a consequence, a more detailed evaluation of the desired fiber angles would allow for tailoring the layup more efficiently, and the structural response would comply closer with reality.

Recent developments in design software included tools such as more elaborate cost estimation systems and draping simulations. The question was now how these tools allowed for the more advanced assessment of a design solution in terms of cost versus structural performance than done previously. In this work, it is investigated whether and in what form a draping model could be used for the cost/weight optimization of composite aircraft components.

Looking at available draping simulations, we can distinguish between two different types of modeling approaches. On the one hand, mechanical algorithms can be applied which use the materials equilibrium equations to drape the material with

the help of an external force. For instance, Boisse et al. [18] and Badel et al. [19] developed finite elements for a woven unit cell and compared the simulation of a draped hemisphere with experiments. Further, Nguyen et al. [20] modeled the fiber rotation, shear and slip of plain weave by means of a truss model. Commercial software packages are available (e.g. AniForm¹ or PAM-FORM²). As all mechanical models, they are based on computationally rather heavy explicit FE code.

On the other hand, kinematic algorithms (also known as mapping or fishnet algorithms) map a unit square of fabric or tape onto a geometric surface. Kinematic algorithms normally do not account for boundary conditions, loads or friction (although some developments included the effects of the blank-holder forces, see Wiggers [21]). These restrictions reduce their application mainly to the draping of dry weave and the hand layup of prepreg. The advantages, however, are the greatly reduced computation time and the reduced model complexity – which is reflected in the reduced amount of input parameters needed. Examples for commercially available packages using a kinematic approach are PAM-QUIKFORM², FiberSIM³, Interactive Drape⁴ or Composite Modeler⁵.

Most of the kinematic codes are based on the work performed by Mack and Taylor who proposed the pin-jointed net idealization [22]. Wang et al. compared the results of a pin-jointed net simulation with experiments for a series of articles, such as a rudder tip, D and nose ribs and flap panels [23]. They concluded that the simulations agreed well with the experiments, although the choice of the initial contact point (seed point) "may result in considerably different draped patterns".

According to Guillermin [24], the use of draping tools should not only allow for a more detailed assessment of the draped fabric, but also for an optimization in terms of total fabric shear deformation, prescribed fiber orientations at control points, unavoidable darts and splices at noncritical areas of the part, and the optimization of the best layup start point. Some drape optimization of woven composites was performed by Skordos et al. [25] who modeled and optimized a hemisphere by means of FE and a genetic algorithm. Thus, wrinkling was minimized by optimizing the holding force distribution.

2 Aims and scope

In this work we resumed Guillermin's idea of drape optimizing composite parts by the use of a kinematic draping software. Hence, we adapted the framework proposed in [17] for the use with a draping simulation. By accounting for the material consumption and process time, it is tried to find tradeoffs between the structural performance of a component and its manufacturing cost.

¹<http://www.aniform.com>

²<http://www.esi-group.com>

³<http://www.vistagy.com>

⁴<http://www.interprot.com>

⁵<http://www.simulayt.com>

The methodology is applied in two steps. First, a draping knowledge database is generated. There, combinations of seed points (location of initial contact between the ply stack and the next layer) and reference angles (the angle between the 1-axis of the prepreg ply and a reference coordinate system) are evaluated in terms of fiber angle deviation, material consumption, cuts and material shear (see Section 3.2). For an explanation of seed point, reference angle, reference coordinate system and fiber angle deviation it is referred to Figure 2. Second, the cost/weight optimization framework picks the best sets of plies during the subsequent optimization. It is tried to find combinations of seed points and reference angles that are optimal from a structural and a cost perspective.

Figure 2: Definition of seed point, reference coordinate system, reference angle ϕ , nominal fiber direction, draped fiber direction and fiber angle deviation at control points.

The methodology is aimed to be used in the preliminary design phase; thus, the output of the optimization is neither a detailed manufacturing documentation nor a ply book. The introduction of a draping model in this phase is rather a way to (a) provide the cost model with more detailed manufacturing knowledge, (b) to perform a structural analysis with fiber angles closer to reality and producibility constraints, and (c) to show that the choice of the draping strategy can influence the cost and weight balance of a component.

3 Method

The proposed optimization framework consists of two parts. First, there is a global cost/weight optimization routine which includes the calculation of the weight, cost and structural performance. Second, this routine is extended by a draping knowledge database which supports the cost estimation of the composite parts.

3.1 The cost/weight optimization framework

The cost/weight optimization framework as illustrated in Figure 3 contains the necessary modules to calculate the objective function and constraints as well as the solver.

Figure 3: The cost/weight optimization framework with the novel draping knowledge database within dashed lines.

As described in the introduction, we decided to use a simplified form of the direct operating cost *DOC* as the objective function. This *DOC* was defined as

$$DOC = C_{man} + p \cdot W \quad (1)$$

where C_{man} represents the manufacturing costs (in €), p is a weight penalty (in €/kg), and W is the structural weight (in kg) of the component. The global optimization problem was formulated as

$$\begin{aligned} \min \quad & DOC \text{ of an aircraft component} \\ \text{subject to} \quad & \text{structural requirements} \\ & \underline{x}_i < x_i < \bar{x}_i, \quad i = 1 \dots n. \end{aligned} \quad (2)$$

with the variables x_i and their lower and upper boundaries $\underline{x}_i$ and $\bar{x}_i$, respectively. The problem given in Equation (2) was transformed to its mathematical formulation

$$\begin{aligned} \min_x \quad & f(x), \quad x \in R^n \\ g_j(x) \leq 0, \quad & j = 1, \dots, m \\ \underline{x}_i \leq x_i \leq \bar{x}_i, \quad & i = 1, \dots, n. \end{aligned} \quad (3)$$

In this case, the cost/weight objective function $f(x)$ and the constraint functions $g_j(x)$ could not be expressed by explicit formulae, since both objective function and constraints were dependent on the output of separate modules. Thus, only the results of the weight and cost estimation modules and the calculation of the structural performance were fed back to the solver.

The cost model seen in Figure 3 was based on the code SEER-MFG by Galorath Inc.⁶. In Table 1, an example for the output of that code is given. Note the level of detail obtained for the different cost contributors. The advantage of using a commercial code was the reliability of the estimation and the broad acceptance in the aircraft industry. The same applied to the structural model. Unlike similar work in this field which relied on closed-form solutions provided by the Engineering Sciences Data Unit (see Curran et al. [26]), a commercial FE package was used for the calculation of the structural performance. Despite the higher computational effort, we believe that the use of ABAQUS/CAE provides greater flexibility in terms of geometry and load cases, especially when dealing with composite structures. It was decided not to include the NDT module described in Kaufmann et al. [16].

Table 1: Example of a manufacturing cost estimation as obtained from SEER-MFG. During the optimization, four decimal places were used for the calculation of exact finite differences.

	min/Unit	Cost/Unit
LABOR TOTAL	1774.6	4436.0
Manufacturing Labor Total	1774.6	4436.0
Setup	0.6	1.0
Direct	1774.0	4435.0
Inspection	0.0	0.0
Rework	0.0	0.0
Assembly Labor Contribution		0.0
ADDITIONAL COST		956.3
Material		711.0
Tooling		0.0
Other		245.3
TOTAL COST		5392.3
ADDITIONAL DATA		
Finished Weight (kg)		8.1
Material Placement (min)		339.5
Cutting Time (min)		20.8
Layup Time (min)		318.7
Tool Closing (min)		950.7
Cure Cycle (min)		285.9
Remove Part (min)		168.8
Part Finish (min)		16.4
Tool Cleaning (min)		12.0

⁶see <http://www.galorath.com>

A solver was chosen that would process the output of these models, not be too sensitive to disturbances in the form of non-smooth objective and constraint functions, and thus lead to a good convergence rate. Otherwise, the choice of solver was arbitrary. For a detailed description of the optimization framework it is referred to Kaufmann et al. [15–17].

3.2 Draping knowledge database

It would be ideal to use a multi-level optimization framework as shown in Kaufmann et al. [17] to find the best draping strategy for each solution in the geometrical optimization. This would, however, involve a very large number of draping calculations with many redundant initial conditions among them. Therefore, it was decided to generate a draping knowledge database *before* the actual optimization was performed. Thus, we sought a set of *best plies* which conformed to the 0, 90 and $\pm 45^\circ$ directions, fulfilled certain criteria and which could be used as the input to the global optimization of the component's geometry. For that purpose Simulayt's Composite Modeler was used.

Composite Modeler is an add-on to ABAQUS/CAE which can map unidirectional and woven composites onto a previously modeled shell surface. Input parameters to Composite Modeler were the type of the material (weave or tape), the extension type (which governs the draping kinematics e.g. by minimizing shear strain deformation energy), seed points, reference angles and material parameters (such as maximum strain, warp/weft angles and warp/weft ratios). The procedure in ABAQUS/CAE was the following: mesh the part, call the draping plug-in, define layup, material and draping properties, export the flat pattern, and map the simulated composite properties back onto ABAQUS sections. All these steps could be performed in batch mode. Further, a recently implemented functionality allowed the export of a range of properties to a text file. In that sense, access to the draping strain, ply thickness, and ply angle in every element was gained before they were mapped back onto sections. This text file was then used for the creation of the knowledge database.

The generation of the knowledge database was done in three steps. First, a ply set with nominal fiber angles (i.e. nominal 0, 90 and $\pm 45^\circ$ plies) was created. Second, sets of deviating reference angles were seeded in various locations of the component. Third, these sets were scanned for combinations of good seed points and reference angles which formed the knowledge database. This scan can be described as follows:

- (i) Consider only feasible sets of seed points and reference angles by limiting the shear angle γ during draping. The latter is depending on the maximum shear angle $\gamma_{\max}$ which is a material property.
- (ii) Select the combinations of seed point and reference angle which conform best to the four nominal plies. The selection is based on an objective function F .

Figure 4 shows a schematic drawing of two flat patterns generated using different seed points. Clearly, it can be seen that the material consumption of the left pattern

Figure 4: Two flat patterns as exported from Composite Modeler. Note the differences in material consumption versus average deviation from a 45° ply.

is higher than the one on the right. On the other hand, the left pattern complies better with a nominal 45° ply than the one on the right. Depending on the objective function F , the solver would choose the left (for minimum fiber angle deviation) or the right pattern (for minimum material consumption).

Obviously, one has different alternatives to define the objective function. One possibility is to use the error between the seeded and the nominal fiber angle distribution, the so-called fiber angle deviation. This norm is given as

$$F_\theta = \|\overline{\theta_{seed}} - \overline{\theta_{nom}}\| \quad (4)$$

where $\overline{\theta_{seed}}$ is a vector containing the simulated fiber angle distribution at the current seed point and reference angle, and $\overline{\theta_{nom}}$ is a vector containing the nominal fiber angle distribution. It might not be necessary to closely follow the nominal fiber angle distribution in all points of the ply. Therefore, control points, a control line or a control surface can be selected in which the norm F_θ is calculated. Hence, a set of best plies which minimize F_θ leads to a solution closer to the nominal fiber angles and to more quasi-isotropic fiber angles. Note that quasi-isotropic layups do not have to be optimal to meet the stiffness criteria. It is, however, common in aircraft design to use $0, 90$ and $\pm 45^\circ$ fiber angles, as non-conform designs would need additional efforts in material characterization and certification.

Similarly, one could define an objective function F_γ as the norm of all in-plane shear components γ in a ply. This norm is given as

$$F_\gamma = \|\overline{\gamma}\|. \quad (5)$$

A set of best plies which minimizes F_γ leads to a better producible solution in terms of drapability, as the risk for wrinkles and likewise problems is smaller.

A third way to define the objective function is to reduce the material consumption, thus minimizing the amount of raw material needed by using

$$F_A = A. \quad (6)$$

Parameter A is the total material consumption as shown in Figure 4. The authors are aware of the fact that F_A might overestimate the amount of material needed and create an upper bound for the material consumption; in fact, tools are available which try to reduce the scrap rate by means of nesting algorithms [27]. The implementation of such a nesting algorithm in the current framework is promising and should be considered for future research activities.

A way to reduce the time of ultrasonic cutting is to minimize the perimeter. In this case, the objective function for the generation of the knowledge database is defined as

$$F_C = C \quad (7)$$

with C being the perimeter of the flat pattern. The draping tool also allows for the introduction of splits and splices. The splits enhance the drapability and minimize the effects of fiber angle deviations. If the ply is not split, however, the cut length is basically constant and its optimization would not make sense.

Thus, the knowledge database consists of draped plies with different seed angles and reference angles, some of the plies being marked with a tag *best ply* and the governing objective function (4)-(7).

4 Case study

It was decided to use a curved C-spar as a test case. This component had a length of 1.2 m, a sweeping web height of 120-150 mm and a flange width of 100 mm. As shown in Figure 5, the load case involved a uniformly distributed pressure on the outer flange corresponding to the cabin pressure of an airliner. Simply supported flanges formed the boundary conditions while the spar had to withstand a maximum strain criterion and a maximum displacement at mid-length.

Figure 5: Geometry and load case of the C-spar used in the case study

First, a "weak" ply was seeded along a curve corresponding to the spar's center line in order to generate the nominal 0° ply. For the generation of the draping knowledge database, a series of seed points was chosen, see Figure 6. The knowledge database generator then swept the reference angle from -90° to $+90^\circ$ in each of the seed points and saved the results in terms of total material consumption, cut length, shear angle and fiber angle distribution.

Figure 6: Eight seed points used in this case study

Two material systems were used. On the one hand, a plain weave prepreg was chosen to provide a high drapability in spite of moderate structural properties. A range of maximum shear angles could be found in the literature; we adopted a value of 30° based on Lin et al. [28]. On the other hand, a UD prepreg would provide high stiffness and strength at a rather low drapability. Thus, a maximum shear angle of 10° was assumed. During the generation of the knowledge database, all plies with shear angles exceeding these values were considered as unfeasible. The material properties are compiled in Table 2.

The best plies of this knowledge database were selected using objective functions F_θ and F_A . We decided not to use the cut length F_C as an objective, as these lengths remained the same unless splits were introduced.

The total framework was implemented by means of the scripting language Python. The main advantage of Python was the seamless integration of ABAQUS/ CAE and Composite Modeler commands. In addition, Python controlled the execution of the cost estimation, the variable handling and not least the draping knowledge database in the form of a Python "shelf database".

SEER-MFG was used for the estimation of the manufacturing cost. This tool had to be adapted in order to estimate the cost of a C-spar based on the inputs from the draping module. In particular, one had to implement and parameterize the cost model in terms of material consumption for all four main directions (0° , 90°

Table 2: Material properties. PW and UD refer to plain weave prepreg and unidirectional prepreg, respectively.

		UD	PW
Young's modulus [GPa]	E_1	151	75
	E_2	8.5	75
Shear modulus [GPa]	G_{12}	4.2	4.2
	$G_{23} = G_{13}$	4.2	4.2
Poisson ratio [-]	ν_{12}	0.30	0.037
Density [kg/m ³]	ρ	1500	1500
maximum shear [°]	$\gamma_{\max}$	10	30
ply thickness [mm]	t	0.25	0.25

and $\pm 45^\circ$), a functionality which was not part of the original SEER distribution. These four ply directions were modeled as following.

- First, the four ply directions were handled separately. Hence, four separate batches of raw material were cut, each rounded off by a (discrete) number of layers. All four batches provided an estimation of the material cost and the cutting time.
- Second, the batches were lumped together for the estimation of layup time, tool closing time, cure cycle duration, part removal and part finish duration, and tool cleaning time. Depending on the complexity of the part, these time estimations were adjusted by a so-called part complexity factor which varied between 0.9 for very simple laminates and 4.3 for very complex components.
- Third, these labor hours underwent a learning curve based on 100 manufactured units.
- Finally, the time-corrected labor hours were converted into manufacturing costs, as can be seen in Table 1. The labor rate of €150/h included overhead cost such as autoclaves and other equipment.

Once the geometry and thus the complexity of the part were set, the layup rate was assumed to be independent of the draping strategy. This was a simplification and shortcoming of the cost and draping tools used. Ward et al. indeed showed that the time to drape a ply can depend on the material, the seed point and the draping sequence [29] by using Hancock's Virtual Fabric Placement software [30]. A material placement model which provides the functionality to calculate the time to drape a ply would therefore be an interesting enhancement for this optimization framework.

In order to reduce the computational workload, a gradient-based method was chosen for the optimization. The *method of moving asymptotes* (MMA) was developed by Svanberg [31] for the purpose of structural optimization and further

enhanced to improve the global convergence [32]. As the overall methodology was intended to be used in the preliminary design phase, the time to solve the problem was crucial for its applicability. Here, we saw the advantage of a gradient-based method over evolutionary algorithms. In addition, MMA existed as a tool called Xopt⁷. Optimization trials were performed as follows:

The selection of the *best plies* for minimum fiber angle deviation F_θ or lowest material consumption F_A was done directly after the generation of the draping knowledge database. This was done in order to reduce the number of FE calculations in this stage of the design chain. Obviously, one could also use all possible combinations of plies during the optimization. The latter was implemented using a genetic algorithm, but not used for this study.

The thickness of the 0° , the 90° and the $\pm 45^\circ$ direction were used as the three continuous variables throughout the optimization of the UD prepreg. Similarly, the optimization of the plain weave prepreg contained two variables, one for $0/90^\circ$ and one for $\pm 45^\circ$. The solver first disturbed the first variable by a small value and calculated the finite difference of the objective function and the constraints. Then the second variable was disturbed, followed by the third. The final step of an iteration was the calculation of a new solution based on the values of the three foregoing finite difference calculations. 20-40 iterations were necessary to reach convergence.

A series of different optimizations runs were performed and analyzed. An overview is given in Table 3. For both material systems, a minimum cost and a minimum weight solution were sought; the two objective functions corresponded to a weight penalty of 0 and ∞ , respectively.

Table 3: Optimization runs performed for the case study. PW and UD refer to plain weave prepreg and unidirectional prepreg, respectively.

number	material	KB	objective function
1	UD	F_θ	min weight
2	UD	F_θ	min cost
3	UD	F_A	min weight
4	UD	F_A	min cost
5	PW	F_θ	min weight
6	PW	F_θ	min cost
7	PW	F_A	min weight
8	PW	F_A	min cost

⁷see <http://www.alfgam.se>

5 Results

In Table 4, the cost and the weight optimization of a unidirectional prepreg with minimum fiber angle deviations are shown. As can be seen, the results were very similar in terms of cost and weight. This is not surprising, as the C-spar was modeled using only additive processes, such as hand-laid prepreg systems. Some differences, however, could be found in the thickness of the 90° and the $\pm 45^\circ$ layers. In particular, the latter was reduced in the case of cost optimization as a direct consequence of the higher material consumption of the 45° layer. Note that the layup time and the tool closing time were the same, as the total thickness was rounded up to the same number of plies.

The optimization results of unidirectional prepreg with minimum material consumption F_A were even more similar, see Table 5. While the direct labor cost was exactly the same, the minor difference in material cost was a result of the slightly different thicknesses of the 90° and the $\pm 45^\circ$ layers.

In Table 6, the results of the cost and weight optimization of a plain weave prepreg with minimum fiber angle deviations are shown. Differences in terms of cost and weight can be seen. This was a consequence of the much thicker $0/90^\circ$ layer in the cost-optimized layup, which led to a significant reduction of material cost. By contrast, the direct labor cost was the same for both optimization runs.

Finally, the biggest differences could be seen in Table 7. The minimum weight solution showed a $\pm 45^\circ$ governed fiber layup, whereas the minimum cost solution was $0/90^\circ$ dominated. This was a consequence of the cost saving potential of this draping set whose plies were selected according to minimum material consumption F_A . Note the differences in material cost for these two solutions, as well as the differences in material cost compared to Table 6.

6 Discussion

As expected, the minimum weight solution always resulted in higher manufacturing cost. For both material systems, the lowest cost was achieved by using the best set of plies corresponding to a minimum material consumption criterion. Similarly, the ply set with minimum fiber deviation accounted for the minimum weight solution. These differences were not too big in this case study. One could imagine aircraft components where the potential for cost reductions could considerably influence the choice of the draping strategy, though. Examples for such parts are:

- (i) Shape optimized parts with tradeoffs between the thickness and the geometry. Examples are stiffened panels, where the stringer shape and stringer pitch is responsible for the cost/weight balance of the overall part, see Curran et al. [13] and Kaufmann et al. [15, 16].
- (ii) Subtractive processes, such as machined aluminium parts, see Kaufmann et al. [15].

Figure 7: Plain weave and UD stacking sequence for a control point in the center of the spar web (depicted as point S3 in Figure 6). Note the differences in fiber angles compared to the nominal angles (given in brackets).

Second, the weight and the cost of the UD prepreg solution were higher than the PW prepreg solution. This was not obvious at first sight, as the optimization of UD prepreg involved more independent variables than the optimization of PW prepreg. A closer look to the local fiber angles of the two material systems, however, gave an indication for a possible reason. Figure 7 shows the fiber angles at the center of the spar web (depicted as S3 in Figure 6). In particular, the fiber angles of the plain weave and the UD prepreg are shown for optimization runs 1 and 5 (weight optimized F_θ ply sets). As can be seen, the plain weave had only a minimal fiber angle deviation compared to the nominal layup, whereas the UD prepreg layup showed significant deviations. This is most obvious for the 90° layers which locally deviate up to thirty degrees as a consequence of the reduced shear deformability. Hence, the big differences in fiber angles compared with the nominal layup resulted in thicker 0° and 90° plies which in turn worsened the cost and weight balance at the disadvantage of the UD prepreg. Note that in reality, this disadvantage would be accounted for by splitting the layers appropriately, which is why a direct PW/UD comparison is not possible here.

The reduced deformability of UD prepreg was also noticed when the knowledge database was generated. Many solutions were unfeasible due to the tight constraint of 10° maximum shear, and the "best" plies with rather high fiber angle deviations were chosen from a highly reduced range of solutions.

For two particular cases, the layup sequence was very much dominated by one fiber direction, i.e. by the $\pm 45^\circ$ direction of the minimum weight solution in Table 6 and by the $0/90^\circ$ of the minimum cost solution in Table 7. There, common lamination rules of at least 10% in each direction were not fulfilled anymore. As a consequence, these rules were implemented in the optimization routine and the results rerun. As expected the solutions became more quasi-isotropic; otherwise no relevant changes could be observed.

Table 4: Optimization run 1&2 - UD - min F_θ

	min Weight	min Cost
weight	7.62 kg	7.63 kg
total cost	€ 5394.29	€ 5392.35
material cost	€ 711.95	€ 710.99
direct labor	€ 4436.01	€ 4435.04
cutting time	21.23 min	20.84 min
layup time	318.68 min	318.68 min
closing time	950.65 min	950.65 min
0° layer	0.50 mm	0.50 mm
90° layer	0.90 mm	1.34 mm
±45° layer	2.54 mm	2.37 mm

Table 5: Optimization run 3&4 - UD - min F_A

	min Weight	min Cost
weight	7.65 kg	7.65 kg
total cost	€ 5360.06	€ 5359.73
material cost	€ 664.35	€ 664.02
direct labor	€ 4449.38	€ 4449.38
cutting time	21.71 min	21.71 min
layup time	318.68 min	318.68 min
closing time	954.38 min	954.38 min
0° layer	0.50 mm	0.50 mm
90° layer	1.50 mm	1.34 mm
±45° layer	2.30 mm	2.38 mm

Table 6: Optimization run 5&6 - PW - min F_θ

	min Weight	min Cost
weight	6.96 kg	7.10 kg
total cost	€ 4905.04	€ 4830.62
material cost	€ 611.29	€ 536.43
direct labor	€ 4062.70	€ 4063.15
cutting time	19.17 min	19.62 min
layup time	294.63 min	294.63 min
closing time	870.74 min	870.74 min
0/90° layer	0.70 mm	2.23 mm
±45° layer	5.30 mm	3.89 mm

Table 7: Optimization run 7&8 - PW - min F_A

	min Weight	min Cost
weight	7.14 kg	7.22 kg
total cost	€ 4863.51	€ 4645.43
material cost	€ 551.37	€ 333.87
direct labor	€ 4081.10	€ 4080.52
cutting time	19.62 min	20.20 min
layup time	300.65 min	300.65 min
closing time	871.56 min	871.56 min
0/90° layer	1.29 mm	5.72 mm
±45° layer	4.87 mm	0.50 mm

Finally, the merit of a solution in terms of direct operating cost DOC was computed. Hence, each cost/weight solution given in Tables 4-7 was recalculated by using Equation (1) and three different weight penalties. In Table 8, the result of this calculation is shown. As can be seen, the best draping strategy depended on the value of the weight penalty. In particular, the best strategy for $p = \text{€}150/\text{kg}$ was a cost optimized C-spar whose plies were chosen with regard to minimum material consumption. For $p = \text{€}1500/\text{kg}$ and $p = \text{€}15000/\text{kg}$, the choice would shift to a weight-minimized spar with minimum fiber angle deviation. There, the benefits of the lower weight outweighed the slightly higher manufacturing cost compared to a cost optimized solution.

Table 8: The solutions of Tables 4-7 compiled in terms of C_{man} , W and $DOC = C_{man} + pW$. Three weight penalties p were applied. The lowest DOC for each weight penalty is marked in bold.

(a) Results for the plain weave prepreg				
	PW - min F_θ		PW - min F_A	
	minW	minC	minW	minC
C_{man} [€]	4905	4831	4864	4645
W [kg]	6.96	7.10	7.14	7.22
DOC [€], $p = \text{€}150/\text{kg}$	5949	5896	5935	5728
DOC [€], $p = \text{€}1500/\text{kg}$	15345	15481	15574	15475
DOC [€], $p = \text{€}15000/\text{kg}$	109305	111331	111964	112945

(b) Results for the unidirectional prepreg				
	UD - min F_A		UD - min F_θ	
	minW	minC	minW	minC
C_{man} [€]	5360	5360	5394	5392
W [kg]	7.65	7.65	7.62	7.63
DOC [€], $p = \text{€}150/\text{kg}$	6508	6507	6537	6537
DOC [€], $p = \text{€}1500/\text{kg}$	16835	16835	16824	16837
DOC [€], $p = \text{€}15000/\text{kg}$	120110	120110	119694	119842

In order to examine the sensitivity of the touch labor cost with respect to the fabric type and mass/unit area, the manufacturing cost of the spar (i.e. the result of optimization run 5) was remodeled with twice the ply thickness. Obviously, the total weight did not change, as the cross-section's thickness remained the same. The number of plies and the cutting time, however, were reduced by 50%; the layup and tool closing times decreased by 49% and 43%, respectively, and the part removal time (which included debuggng after each debulking step) decreased by 41%. As

expected, the total cost did not halve if twice the ply thickness was used; it dropped from €4905 to €3334. Thus, 32% manufacturing cost could be saved.

The use of one general hourly labor rate might not be adequate throughout all manufacturing processes (i.e. ply cutting, tool preparation, layup, debulking, curing, part removal and inspection), since manual processes are discriminated in terms of cost. In our opinion, however, SEER-MFG provided the best functionality and cost sensitivity along with a strong acceptance in the aircraft industry. Thus, we refrained from replacing the SEER-MFG algorithms by an own implementation. In addition, every other definition of labor rates would be company-specific and not as general in its use.

A more detailed study is presented in Kaufmann et al. [33], where five different material systems and the effect of changes in labor rates, production quantities and material costs are examined.

7 Conclusions

An existing cost/weight optimization framework for composite structures was extended by the implementation of a draping simulation tool. Thus, an optimal draping strategy in terms of seed point and reference angle was selected in each iteration of the geometric cost/weight optimization. These optimal draping strategies which led to *best plies* could be evaluated with different objectives, such as minimum material consumption, minimum cut length, or minimum fiber angle deviation examined at a predefined set of control points. The manufacturing cost was calculated by an established cost estimation program. These cost estimates were modified in a way that inputs such as material consumption and cut length were directly imported from the draping simulation. Hence, the merit of a draping strategy could precisely be evaluated in terms of manufacturing cost and structural performance.

In a case study, a curved C-spar built of plain weave prepreg or unidirectional prepreg was cost and weight optimized while keeping the set of best plies constant. For both material systems, the cost-optimal solution was a set of best plies which was chosen according to minimum material consumption objectives. Similarly, the weight-optimal solution was achieved with a set of best plies which had the least fiber angle deviation compared to a nominal layup. It was concluded that the plain weave prepreg component performed better than the unidirectional prepreg component. This was a consequence of the reduced drapability of the UD material. Hence, the material systems were not quite comparable. In practice, one would introduce a number of splits in the UD plies in order to minimize the effects of fiber angle deviations.

A certain comparison was done anyway on the level of direct operating cost. It could be seen that the optimal draping strategy shifted when different weight penalties were applied. For a high weight penalty, for example, the plain weave prepreg with a ply set of minimum fiber angle deviation was found to perform the best. For that particular case, a stacking sequence close to the nominal fiber angles

was favorable, whereas the effects of the reduced material consumption played a minor role for the value of *DOC*.

The benefits of the integration of this draping tool were as follows. First, drape-corrected fiber angles were used instead of nominal $0/90/+45/-45^\circ$. This fiber angle deviation had a substantial impact on the structural performance of the component and should therefore not be neglected. Second, the use of a feasible draping strategy leads to producible design solutions already in an early design phase. Thus, draping tools such as Composite Modeler are on their way to become a standard in the design process of aircraft manufacturers and component suppliers, and should therefore also be included in an optimization framework. Some drawbacks exist, though. The draping database, for example, can only be generated when the overall geometry of the component is frozen. Hence, the framework would appear in a second step of the preliminary design phase – after the completion of a less detailed cost/weight optimization as presented in previous articles by the same authors. Further, the time to place a ply is independent of the draping strategy itself. This is a shortcoming of the combination Composite Modeler and SEER-MFG used in this work.

Two areas of future work were identified: First, it would be interesting to implement a nesting algorithm in order to estimate scrap rates and material consumptions closer to reality. Second, a draping model could be used which estimates the exact time of placing the material based on the draping route. Thus, the labor cost could be calculated more accurately by taking into account the intrinsic effect of the draping strategy.

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