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Components made in composite material can lower the weight of structures significantly. The higher production and material cost, however, require the application of novel design strategies which allow for the cost-efficient production of these components. A methodology for a combined cost/weight optimization of composite components is presented herein. The objective function is formed by a simplified form of direct operating cost, i.e. by a weighted sum of the manufacturing cost and the component weight. The parameter that governs the balance between manufacturing cost and weight is called weight penalty and incorporates the effect of fuel burn, environmental impact or contractual penalties due to overweight. In addition, a non-destructive testing model is implemented that calculates design allowables of a laminate based on ultrasonic scan parameters. In a case study, the effect of the laminate quality on the direct operating cost is discussed. It is investigated how the permissible flaw size and therefore the scan pitch of a composite laminate can influence the optimal solution in terms of cost and weight; thus, the manufacturing cost, the non-destructive testing cost and the weight of a component can be balanced by optimizing the laminate quality in an early design phase. The optimization framework also contains a draping simulation in combination with a detailed cost estimation package and the calculation of the structural performance based on FE. First, a draping knowledge database is generated in which combinations of seed points and reference angles are evaluated in terms of fibre angle deviation, scrap, ultrasonic cuts and material shear. Second, the cost/weight optimization framework picks the best sets of plies during the subsequent optimization. By means of parametric studies it is shown that the design solution strongly depends on the magnitude of the weight penalty. It is also shown that the non-destructive testing affects the cost and choice of design concept and the permissible flaw size should be altered in order to save both weight and cost. Finally, 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: Composite Structures, Optimization, Operating Cost, Non-destructive testing, Finite element analysis

1. INTRODUCTION

Composite structures can lower the weight of structures significantly. By designing 40% of the components in carbon fibre reinforced plastics, for example, 1500 kilograms were saved in the centre wing box of the Airbus A380, see Marsh\(^1\). The switch to composite materials, however, implies an increased cost for material, processing and non-destructive testing. In addition, the design procedures, the quality management and the production of the components are generally more complex compared to metallic structures. These challenges were identified and described by Gutowski et al\(^2\), Rais-Rohani et al\(^3\) and Soutis\(^4\). It was concluded that (instead of minimizing the weight) one should take the total lifecycle of a component into account when choosing the appropriate material system, manufacturing process and overall geometry.

The increased production cost often attributed to composite materials requires the application of cost-effective design strategies. Traditionally, the structural design and the manufacturing planning are done sequentially. This may work for

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metallic structures; for composites, however, the design is strongly influenced by the choice of the material, the manufacturing process and the structural requirements. The design is then based on attributes like material properties, manufacturability, series size and stressing guidelines, while cost and potentials to save cost play a minor role.

Nevertheless, the manufacturing cost should be included in the early design phase of the component design of primary composite structures. Therefore, a cost/weight optimization framework was developed within the European FP6-ALCAS project – acronym for Advanced Low Cost Aircraft Structures; the aim was the optimization of structures with the direct operating cost or the life-cycle cost on a component level as the objective function. In the presented approach, the objective function is formed by a weighted sum of the manufacturing cost of the component, in-production and in-service inspection cost and a specific fuel burn cost. Balancing cost and weight objectives is not a simple task. First, one needs to consider the designer's perspective which could lead to different weighting factors. The amount of fuel burned by an additional kilogram structural mass, for instance, would lead to a different specific cost per kilogram than the revenue that could be achieved by one kilogram more freight during the lifetime of the structure.

This paper is a summary of earlier work where a methodology was developed for integrated cost/weight design optimisation of composite structures\textsuperscript{5,6,7,8,9}. The methodology is far from complete but it shows a possible path towards a more integrated design strategy for composite structures where cost, weight and other performance metrics can be integrated into one scheme hopefully giving a better design, at least in the preliminary design stages.

![Figure 1. The optimization framework in which the production cost and the weight (by means of a weight penalty in euro/kg) are part of the objective function.](image)

### 2. METHODOLOGY

The methodology consists of several parts as schematically illustrated in Fig.1. The design is described in terms of features; shells with thickness, layers and fibre angles, and stiffeners with lengths, thicknesses, layers, etc. These are used as design variables in several of the other toolboxes building up the entire framework. The solver is an optimisation engine which could be based on e.g. evolutionary or gradient-based algorithms. A finite element (FE) model is used to calculate the structural response and the manufacturing cost is calculated with a separate software, just as the non-destructive testing cost. Finally, there is a separate database used to find the most appropriate draping strategy.
2.1 Optimisation problem

Our problem for the combined optimization of manufacturing cost, NDT cost and weight is formulated as

\[
\min \quad DOC \text{ of aircraft component} \\
\text{subject to} \quad \text{structural requirements} \\
\quad x_i \leq x_j \leq \bar{x}_i, \quad i=1...n
\]

where \( DOC \) is the share of the direct operating cost, \( x_i \) are design variables, and \( \underline{x} \) and \( \bar{x} \) are their lower and upper limits, respectively. The objective function \( DOC \) was defined as

\[
DOC = \alpha_1 C_{\text{man}} + \alpha_2 C_{\text{ndt,prod}} + \alpha_3 N C_{\text{ndt,serv}} + pW
\]

where \( C_{\text{man}} \) is the manufacturing cost of the component, \( C_{\text{ndt,prod}} \) and \( C_{\text{ndt,serv}} \) are costs for non-destructive testing in production and service, \( p \) is a weight penalty or a specific fuel burn (in \( \text{€/kg} \)) and \( W \) is the structural weight (in kg). The parameters \( \alpha_i \) incorporate calibration factors due to depreciation, overhead cost and other adjustments, and \( N \) is the number of regular inspections during the lifetime of the component. Throughout this study, the parameters \( \alpha_i \) are set equal to 1.

As mentioned above, the optimization framework contains several modules which can be activated when necessary. For instance, the NDT module and the draping module are only applied to composite structures, whereas the manufacturing cost, the weight estimation and the calculation of the structural performance in FE are necessary for both composite and metallic structures. Note that this framework could easily be enhanced by additional modules. Examples of additional modules are tools for estimation of repair cost or for prediction of the inspection interval. The optimiser used in this work is a variant of the method of moving asymptotes (MMA)\(^{10}\) implemented in the software XOPT\(^{11}\).

2.2 Design variables and features

An example of what is used as features and design variables is depicted in Fig.2. It is a skin/stringer element (a generic panel of the upper cover of an airliner wing), referred to as a single skin element, limited by its adjacent transversal and longitudinal stringers. The features of this skin/stringer panel are that it consists of one flat shell with a certain thickness. It has two stringers of the same dimension. Each stringer is characterised by flange widths and web heights. Each flange and web thus has an area. The intersections between the webs and flanges are radii, that in the case of NDT requires special inspection techniques. One could use a discrete ply table as design variables for the skin, but in the case of optimisation in the preliminary design phase it is usually more efficient to merge the plies in the four nominal directions 0, 90, 45 and -45 degrees and to use four thickness variables \((x_1-x_4)\). The upper and lower limits of the thickness variables should be chosen such that the industrial specifications are maintained. Thus, one could guarantee that there are at least one ply in each direction (the lower boundary for \( x_1 \) to \( x_4 \) is 0.26 mm) and that there is at least 10% plies in each direction. The other variables, such as the web height \((x_8)\), the flange width \((x_6)\), and the pitch \( x_7 \) (the distance between the stringers), would also usually have upper and lower bounds.

![Figure 2](image-url)  
Figure 2 Design variables of the skin/stringer panel. Variables \( x_1-x_4 \) refer to ply thicknesses in [0/90/45/-45], direction.
2.3 Structural analysis of constraint functions

The methodology is intended to be applicable to arbitrary composite parts, which makes a standardized procedure from CAD to the final input file necessary. In this work, the model was imported to ABAQUS/CAE and parameterized with the help of Python scripts. Python scripts allowed the creation and modification of the shape and properties of the ABAQUS model, the submission of ABAQUS analysis jobs, and the reading from output databases. In this case, the plate size and the stringer cross-sections were changed according to the actual variables, the ply tables were generated, the part was re-meshed, the analysis job was started and the output database post-processed.

The analysis type depends on the structure and loading condition. The output required make up the constraint functions. This could be stiffness (often stated as maximum displacement conditions) or failure criteria. In this work we have used the maximum strain criterion and its related failure indices, stiffness constraints and buckling loads.

2.4 Manufacturing cost

Manufacturing cost can be estimated by the type and attributes of manufacturing operations and processes. Examples are the stacking of prepreg plies, debulking (consolidation of the prepreg plies in regular intervals, typically every fourth ply), consumables, curing or tooling. Each process represents material cost and time which can be translated into labour costs. The sum of all cost plus an overhead represents the total cost to manufacture the component. This kind of feature-based model is easy to parameterize, as features can be added, removed or modified. The commercially available cost estimation software SEER-MFG incorporates all these capabilities and is therefore used herein. Similar to the approach taken for the FE calculation, an initial model is built up in the graphical user interface of the software, see Fig.3. This model contains all the necessary assumptions and work steps of the manufacturing process. It is exported to a text file, parameterized in terms of the variables $x_i$ and prepared for running in command line mode, the so-called server mode. The cost of manufacturing depends to a large extent on the same features as structural and NDT models.

![Figure 3 The definition of the stringer geometry in the graphical user interface of SEER-MFG.](image-url)
2.5 Weight estimation

The estimation of the weight is done by a simple calculation of the part volume in any given iteration, based on the CAD geometry, the material properties and the actual variables $x_i$.

2.6 Inspection cost and strategy

Nowadays, the design of composite structures is generally not performed considering the non-destructive testing (NDT) aspects. In order to capture the lifecycle cost of a composite component better, NDT should play a role already during the early development phases. Therefore, the optimization methodology was enhanced by the implementation of an NDT module. This model calculates the cost for the scanning operation based on the features of the structure. The shell, flanges and webs require a certain time for scanning depending on their area and scan pitch. The radii require a different scanning method that depends only on the length of the radii in the structure.

Many of the allowables for structural design are based on coupon tests with material containing a certain level of porosity or flaws. Novel in this work is the variation of the quality assurance level of the material. A higher scan resolution in ultrasonic testing due to a smaller scan pitch, for example, could detect lower porosity levels and in-production defects. This in turn leads to a higher “guaranteed quality level” of the laminate with higher scan cost per surface area as the consequence. Hence, the scan pitch of an ultrasonic C-scan was introduced as a variable, depicted as variable $d_k$ in Fig.4. In an in-house developed knowledge-based model, the NDT cost was calculated according this scan pitch.

![Figure 4](image)

Figure 4. Scan path of different NDT features, such as a radius and a flat panel. The smaller the scan pitch $d_k$ is, the higher the probability to detect smaller flaws in the laminate.

The probability of detection never reaches 100%. Instead, confidence levels based on the material, the NDT method and the thickness of the material are used; quoted levels are 90% or 95%. Typical stochastic models used are the Gamma distribution or the two-parameter Weibull distribution. For the Weibull distribution, the cumulative distribution function of the probability of detection ($POD$) is given as

$$POD = 1 - e^{-\left(f / \lambda \right)^k}$$

where $f$ is the flaw size, and $\lambda$ and $k$ are two shape parameters. A typical curve plot for different settings of $\lambda$ is shown in Figure 5.
As can be seen in Fig.5, the **POD** is higher for thinner laminates (the actual value depends on the material, the stacking sequence and the NDT method) and for larger flaw diameters. Today's 6 mm flaw diameter that is used in the aerospace industry would require a scan pitch $d_k$ of approximately 2 mm, the latter having a direct influence on the NDT costs. By varying the permissible flaw size, the quality of the laminate becomes a design variable and the material design strength is affected accordingly. This is an effect of that if a coarser scan pitch is used, the NDT method is only able to detect larger flaws with a maintained **POD**. The design allowables were adapted accordingly, as the scan pitch had a direct influence on the detectable size of a possible flaw.

One could use the porosity as a strength parameter such that increased porosity leads to lower strength. This requires finding an appropriate model matched by experimental data. Another version is the one used by Kaufmann et al. which relates a flaw size both to the NDT cost and the strength of the material. A larger admissible flaw size means lower NDT cost due to the coarser scan pitch for a given **POD**, but lower strength due to larger acceptable flaw sizes, and vice versa. The resulting algorithm is based on that the thickness $t$ and the maximum allowed flaw size $f$ form the inputs to the NDT module. In the first step, the scan pitch $d_k$ is adapted until a desired probability of detection is met. The direct cost for non-destructive testing $C_{NDT}$ is a function of the scanned area (length $l$ and width $w$) and the scan pitch $d_k$. Simultaneously, the strength reduction is calculated and fed into the FE module where the constraints for the optimization are computed.

### 2.7 Draping simulation and expert knowledge base

In most structural analysis work only nominal fibre angles with 0, 90 and ±45° are used. In reality, particularly when manufacturing double-curved components, the manufactured fibre angles cannot match these nominal fibre 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 fibre angles. As a consequence, a more detailed evaluation of the desired fibre angles would allow for tailoring the layup more efficiently, and the structural response would comply closer with reality.

The manufacturing parameters of a composite layer modelled in SEER-MFG, such as the draping strategy, do not necessarily match the knowledge of the production expert. These parameters should be adapted during the optimization of the component, in order to achieve the lowest possible production cost for a given geometric design solution. In order to model the fibre angles of a complex composite part, a detailed draping simulation (using Simulayt’s Composite
Modeler) was implemented in the optimization framework. The advantages of Composite Modeler were the seamless integration into ABAQUS/CAE, the parameterisation with Python and the short calculation time due to the kinematic draping code based on the pin-jointed net algorithm. The output from this model was the fibre angle distribution and an unfolded outline of the draped ply, the so-called flat pattern. The flat pattern was post-processed in order to calculate the length of the ultrasonic cut, the ply area and the material consumption (the area of a surrounding rectangle including ply area plus waste). Thus, the draping module affected both the cost model (material consumption, ultrasonic cutting, and number of plies) and the structural model through the fibre angle after draping, number of plies). As a consequence, the impact of a draping strategy, i.e. the seed point (location of initial contact between the ply stack and the next layer) and the reference angle (angle between the new layer's 1-axis and a reference coordinate system) could be examined in terms of cost and weight.

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 fibre angle deviation, material consumption, cuts and material shear. For an explanation of seed point, reference angle, reference coordinate system and fibre angle deviation, see Fig.6. Second, the cost/weight optimization framework picks the best set 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.

It is important to realise that the draping strategy affects both the structural performance (and thus also the weight and operation cost) and the cost of manufacturing. Figure 7 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 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, the solver would choose the left (for minimum fibre angle deviation) or the right pattern (for minimum material consumption). There are several possible objective functions for this scheme of choosing draping strategy. One strategy could be to minimise the fibre angle deviation in order to get as close as possible to the nominal fibre distribution of 0, 90, 45 and -45 degrees. Another strategy could be to minimise the prepreg shear during draping thus avoiding manufacturing problems like wrinkling. A third option could be to minimise the material consumption and/or the cutting lengths in order to save manufacturing cost.

3. CASE STUDY #1 – COST/WEIGHT OPTIMISATION

The aim of the first case study was to benchmark the framework for the cost/weight optimization. It was chosen to perform parameters studies by means of the generic skin/stringer element as shown in Fig. 2. The loading condition is a pure compression load along the stiffeners implying that there are both (material) strength and buckling constraints, although they do not necessarily have to be active at the same time. Both the shell and the stringers are made from composites thus having 4 separate design variables for the layers. In particular, it was focused on the trade-off between the stringer pitch and the thickness and the layup of the skin. The parameter study is based on varying the weight penalty $p$, which can be interpreted as the fuel burn cost per unit structural weight. Kaufmann et al. estimated a value for $p$ for a commercial airliner to approximately €1000-2000/kg. In this case, the cost of NDT was not included, only the manufacturing cost and the operation cost. The direct operating cost, the objective function, was thus formulated as

$$DOC = C_{man} + pW$$

(4)

In Fig.8, the variables are shown as functions of the weight penalty. A shift in configuration can be seen at a weight penalty of about €600-10000/kg. There, the "coarsely stiffened skin" changed to a "densely stiffened skin". Note that the variables $x_1$-$x_4$ were added and plotted as a single curve to facilitate the understanding of the figure. Generally, the layout was 0° dominated.

Figure 8 Design variables as a function of the weight penalty. $x_1$-$x_4$ are added and plotted as one variable, the skin thickness.
It could be concluded that the manufacturing cost for an increased number of stiffeners was higher than for a bulky skin (low-cost solution). On the other hand, the densely stiffened skin provided lower weight, despite the much higher manufacturing cost (low-weight solution). For a better comparison, the two opposing designs are illustrated in Figure 9.

![Figure 9 Coarsely stiffened low-cost and densely stiffened low-weight solution.](image)

The same type of optimisation runs were performed for an all-aluminium design. In that case, the shift from a low-cost to a low-weight configuration occurred at a weight penalty of €10-1000/kg, i.e., at a considerably lower fuel burn cost. In terms of direct operating cost (DOC), the metallic panel is overall cheaper for weight penalties below approximately €5000/kg. Thus, with increased fuel prices, the composite version will actually be cheaper over the lifetime of the aircraft component, despite having a considerably higher initial price.

### 4. CASE STUDY #2 – EFFECT OF QUALITY LEVEL

The effect of the implementation of quality management in the optimization framework was first shown by means of a case study. Here, the trade-off between cost for NDT and the guaranteed laminate quality was examined for the skin/stringer element in Fig.2. For the sake of simplicity, any depreciation factors and cost adjustments were neglected (i.e. $\alpha_1 = \alpha_2 = \alpha_3 = 1$ in eq.(2)), and the same equipment and operator rates for in-production and in-service inspection were applied. The prescribed probability of detection was set to 95%. Here, five regular inspections during the lifetime of the aircraft were assumed. Therefore, the objective function appears as

$$DOC = C_{man} + C_{ndt,prod} + 5C_{ndt,ser} + pW$$  \hspace{1cm} (5)

The strength reduction was calculated using two models, one for porosity and one for flaws, here based on open hole compression strength. Based on the work on notched specimens by Soutis et al\textsuperscript{12}, the strength degradation of a flaw size other than 6 mm was modelled by the law

$$\hat{\sigma}_f = \hat{\sigma}_0 (1 - A(f - 6))$$  \hspace{1cm} (6)

where $\hat{\sigma}_f$ is the updated material strength due to flaws, $\hat{\sigma}_0$ is the material strength at a standard flaw size of 6 mm, $A$ is a material specific strength degradation constant and $f$ is the permissible flaw size. The strength degradation due to porosity was defined as a function of the thickness. Similar to the work published by Uhl et al\textsuperscript{13} the calculation of the updated material strength due to porosity was done according to the relation

$$\hat{\sigma}_p(t) = \hat{\sigma}_0e^{B(t-t_0)}$$  \hspace{1cm} (7)

where $\hat{\sigma}_p$ is the material strength of a laminate with thickness $t_0$, $t$ is the thickness of the laminate and $B$ is a material parameter. The structural model was then updated using the minimum of the calculated material strengths, i.e.

$$\hat{\sigma} = \min(\hat{\sigma}_f, \hat{\sigma}_p)$$  \hspace{1cm} (8)

Optimisation runs were performed with three different values of the weight penalty; $p = 0$/kg, $p = 1500$/kg and $p$ approaching infinity, corresponding to a low-cost design, a design with a reasonable lifetime fuel burn cost for a commercial airliner\textsuperscript{5} and a low-weight design, respectively.
For low-cost design ($p = €0/kg$) the minimum direct operating cost ($DOC$) is obtained by allowing the permissible flaw size to increase from the standard 6 mm to 16 mm$^3$. This considerably lowers the NDT cost (46% of the baseline when using 6 mm flaw size) but it has no effect on the operation cost since $p = 0$. Using an even higher permissible flaw size increases the manufacturing cost since the reduced material strength requires additional material to carry the mechanical loads.

For the intermediate design ($p = €1500/kg$) the situation changes since weight becomes more important for the $DOC$. As for the previous case, the objective function is the highest for the smallest flaw size (2 mm) due to the high NDT cost. As the panel thicknesses are constrained by the active buckling condition, no weight or cost saving is possible for this laminate quality. As long as buckling governs the design, an increased flaw size mainly results in lower NDT cost while the weight and the manufacturing cost remain the same. At a flaw size of 12.4 mm, the maximum strain constraints also become active, and the $DOC$ achieves its minimum at 96% compared to the baseline (6 mm flaw size). Any increase of flaw size results in increased weight and manufacturing cost, thus forcing the objective function to increase.

The low-weight design ($p$ very high) is again different. As the manufacturing and NDT costs are negligible in this case, the $DOC$ only depends on the weight. As anticipated, the optimum laminate quality is found at very small flaw sizes, and both structural constraints are active.

5. Case study #3 – Materials selection using optimisation

For this case study, a double curved C-spar (a representative fuselage component of a next generation twin-aisle airliner) was chosen as depicted in Fig.10. The loading conditions and constraints are arbitrary for the methodology and here therefore much simplified for the sake of reduced computation time. The spar had simply supported boundary conditions at the edges of the inner flange and it was loaded by a uniformly distributed pressure at the outer flange. The other constraints included a maximum displacement of the outer flange and material-specific strain and stress limits. This case study also includes the draping knowledge database.

Figure 10 Double curved C-spar as used in this project. Shown are 8 different seed points for the draping of a composite ply. Each seed point results in different fibre angles after draping, and in a different consumption of raw material.
As the baseline, the C-spar was cost-optimized using the objective function

\[
DOC = C_{\text{man}} + C_{\text{ndt,prod}} + pW
\]  

(5)

In particular, the comparison of the different material systems and the location of the break-even points were in the focus of this study. Only recurrent costs were considered first. Non-recurrent costs (such as the tooling cost) were included in a second step. In particular, the otherwise arbitrary production quantity should reflect a mature manufacturing process in combination with reasonable depreciation cost for tooling. The direct labour rate is fully built-up, i.e. it contains the cost for manual labour, machines and equipment, and overheads.

Four material systems were chosen for the optimization and comparison:

- Machined aluminium.
- Two RTM6/NCF reinforcements, one with UD reinforcement and one with a bi-axial reinforcements of either [0/90] or [±45].
- An M21/T800 plain weave prepreg.

Figure 11 summarizes the results of the baseline scenario for aluminium and composites. Results depicted with ▼ refer to cost-optimized solutions; △ refers to a weight-optimized solution. In the following, some of these results are discussed.

As can be seen, the aluminium component was the most cost-effective solution for small weight penalties (i.e. the focus was on cost optimization). For higher weight penalties, the RTM system should be preferred. Note that the much higher manufacturing cost of the prepreg structure in combination with limited weight benefits affect that material system adversely.

In Fig.12, the layup of the two RTM (UD) solutions is shown in detail. Note how the design solution is governed by performance and cost criteria. To the left in Fig.12, the unidirectional NCF/RTM layup of the weight optimized C-spar is
shown. In the right figure, the solution for the same material system, although optimized for lowest manufacturing cost is given. As can be seen, there is a distinct change from a 45 degree dominated to a 90 degree dominated solution. The underlying reason for that particular result is the lower material cost of the 90 degrees layer due to the smaller waste of raw material.

Figure 12 Result for weight and cost optimized UD fabric for RTM

6. DISCUSSION AND CONCLUSIONS

An integrated cost/weight optimization framework was proposed and exemplified by means of case studies. The scheme consists of several toolboxes, some being state-of-the-art commercial software as used already in industry, while other are in-house due to lack of commercially available software. It has been built up so that each toolbox can be interchanged for any other equivalent software, e.g., another FE-solver. It is also constructed in way that more toolboxes can be added. There are many more things to consider before a scheme of this type is ready to handle total life cycle cost, such as maintenance and end-of-life costs.

In the first case study the procedure was tested on a compressively loaded skin/stringer element. The introduction of a weight penalty enabled cost and weight to be merged into one single objective function. Nevertheless, this concept has to be challenged. First, the quantification of the weight penalty is difficult and depends on the viewpoint of the optimizer, the aircraft type and the operational profile. It should be adjusted according to the weight saving potential of the part to be optimized. The results were highly dependent on the weight penalty and certainly showed that the ideal choice of the design solution was neither low-cost nor low-weight but rather a combination thereof. It was shown that the merit of a design solution was clearly sensitive to the prescribed weight penalty. According to the literature, weight penalties of €1000-2000/kg were reasonable. In this range, there is a need for an integrated cost/weight optimization.

In the second case study the effect of inspection cost was added and it was shown how the quality assurance aspect could be included in the preliminary design stage. Starting from a standard flaw size, the effect of the laminate quality on the objective function was investigated. The optimal flaw size depended on the structure, the material properties, the load case and the weight penalty. Hence, it was shown that cost savings were possible by revising the laminate quality already in the design phase. The conclusions (suggesting that the permissible flaw size does not have to be 6 mm) should be viewed as specific to the assumptions and analysis made and they may not be valid when, for example, fatigue is taken into account. Further work is needed in this area before any general conclusions can be made.

In the third case study the scheme was used to evaluate different material systems. The selection of the material system should be based on the cost saving potential during manufacturing and operation, since neither design for lowest cost nor design for lowest weight necessarily reflected the true objectives of the designer. Using a simplified form of direct operating cost, it was shown how the choice of the material system depended on the applied weight penalty. The prepreg
material suffered from significant drawbacks when it came to cost-efficiency. The plain weave had much higher touch labour in combination with very little or no weight benefit.

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REFERENCES