INTEGRATED COST/WEIGHT OPTIMIZATION OF COMPOSITE SKIN/STRINGER ELEMENTS

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Abstract

In this paper, a methodology for a combined cost/weight optimization of composite elements is proposed. The methodology is similar to the work of Curran et al. [1], where the objective function is formed by manufacturing costs and a so-called weight penalty. This weight penalty could include the effect of fuel burn, environmental impact or contractual penalties due to overweight, and depends on the view of the "optimizer". In our approach, the analytical cost model is replaced by a commercial software package that allows a more realistic model of the manufacturing costs.

In the spotlight is a parameter study, in which the weight penalty is varied from zero to infinity, literally varying from pure cost to pure weight optimization. This is done for three material configurations: a metal/metal, a composite/metal and a composite/composite skin/stringer panel. It is shown that the design solution depends on the magnitude of the weight penalty and that – depending on this magnitude – another material configuration has to be regarded as the optimum.

1 Introduction

Designing aircraft structures is challenging aerospace engineers more than ever before, since today's performance requirements necessitate the full application of carbon fibers for primary structures. This shift to composite materials lowers the structural weight significantly; the drawbacks, however, are increased manufacturing costs. Through cost-effective design, structural engineers have to find tradeoffs between the minimum weight and the minimum cost solution, two extremes that often contradict each other. Therefore, the focus should not only be on pure weight reduction, but rather on a combined minimization of manufacturing cost *and* structural weight.

Weight savings are directly associated with reduced fuel consumption and increased payload, while reduced manufacturing costs have an impact on the acquisition cost. In order to find the most cost-effective design a comparative value has to be defined which is used to evaluate the quality of a design solution.

A straightforward approach is the use of a reduced type of direct operating cost (DOC) for this purpose. This DOC combines manufacturing costs and the weight by the introduction of a weight penalty; this is used as the objective function of a multidisciplinary design optimization (MDO) scheme. Curran et al. recently investigated this optimization approach with DOC as the objective function; their review article [1] gives a broad overview of what has been done within cost estimation. They also described how DOC was simplified for optimization purposes; see [2].

The magnitude of the weight penalty, however, is not simple to define as cause and effect of weight reduction depend on the perspective in which the methodology is used. The reduction of pollution (environmental impact), a decrease in fuel cost or the aim to maximize the payload would lead to very different settings of the weight penalty, thus resulting in different design solutions for a reference geometry.

In this paper, the methodology of Curran et al. is extended to the cost/weight optimization of generic composite elements and exemplified by means of a case study, i.e. the skin/stringer element. The location of the minimum cost/weight solution with respect to the analysis with different material properties, manufacturing techniques and cost allocations is studied; of main interest is the comparison of an all-metal, a metal/composite and an all-composite panel.

2 Method

As described in the introduction, the objective function of the optimization problem was defined as

$$DOC = MFC + p \cdot W, \qquad (1)$$

where *MFC* represents the manufacturing costs, *p* a weight penalty and *W* the structural weight of the element.

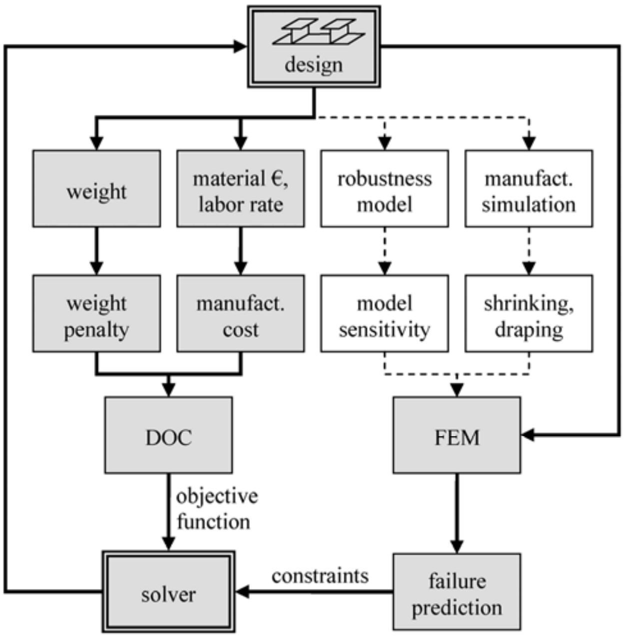


Fig. 1. The optimization loop. Dashed lines and modules are model extensions. They will be implemented in a later phase of the project.

The optimization routine is illustrated in Fig. 1. The currently implemented modules are depicted in grey color. They comprise

1. the geometrical set-up/design variables
2. an FE model
3. a weight estimation module
4. a cost estimation module and
5. the solver

These modules are identified in the sections below. Dashed lines and modules are planned as model extensions; they are described in the section *Future Work*.

The optimization problem can be formulated in mathematical terms as

$$\begin{array}{ll} \text{min} & DOC \text{ of a composite element} \\ \text{subject to} & \text{prescribed load case} \\ & \underline{x}_i \le x_i \le \overline{x}_i, \quad i = 1 \ldots n. \end{array} \qquad (2)$$

with the variables x_i, and $\underline{x}_i$, $\overline{x}_i$ as the lower and upper boundaries. In this study, the methodology was tested on the so-called skin/stringer element.

2.1 The geometrical set-up/design variables

The skin/stringer element (a generic panel of the upper cover of an airliner wing) is referred to as a single skin element, limited by its adjacent transversal and longitudinal stringers. Instead of varying a discrete ply table, the plies in the four directions were merged to four thickness variables. Hence, all laminates of the model are midplane symmetrical with a simple [0/90/45/-45]s stacking sequence. This layout is not used in that form in actual aircraft construction; the advantage of this specific stacking sequence, however, is its general usability for optimization purposes and parameterization. The upper and lower limits of the thickness variables have to be chosen such that the industrial specifications were maintained. Therefore, it has to be guaranteed that there is at least one ply in each direction (i.e. the lower boundary for *X1* to *X4* is 0.26 mm) and that there is at least 10 % plies in each direction. The variables of the model are shown in Fig. 2.

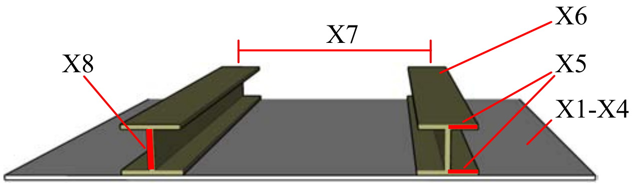


Fig. 2. Variables of the skin/stringer panel. Variables *X1-X4* refer to ply thicknesses in [0/90/45/-45]s direction.

The stringer pitch was assumed to influence the total cost of the panel. Therefore, it was decided to vary the panel's width and to optimize on *weight per unit width* and *cost per unit width*, respectively.

The eight variables and corresponding limits are compiled in Table 1. Note that *X3* and *X4* are equal due to symmetry.

Continuous thickness variables have been used to improve the overall convergence. A possible mismatch with the prepreg ply thickness of 0.26 mm has been accepted.

Table 1. Variables and corresponding upper and lower limits for material configuration b) metal-composite.

	$\underline{x}_i$	$\overline{x}_i$	description
X1	0.26	8.00	0 deg skin
X2	0.26	8.00	90 deg skin
X3	0.26	8.00	45 deg skin
X4	= *X3*		-45 deg skin
X5	5	50	stringer width
X6	1	25	profile thickness
X7	100	300	stringer pitch
X8	20	60	stringer height

2.2 FE model

The methodology was intended to be applicable to arbitrary aerospace parts, which made a standardized procedure from CAD to the final input file necessary. Therefore, the model was imported in 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, plate size and stringer cross-section were changed according to the actual variables, prepreg ply tables were generated, the part was remeshed and the analysis job was started. For details regarding the ABAQUS Scripting Interface, see the corresponding manuals [3].

The model is constrained by periodical boundaries along the sides and meshed with shell elements of the type S4R. The introduction of the compressive loads has been realized by two rigid bodies, simulating the adjacent frame structure. The rows of rivets were approximated by tie constraints, thus preventing any separation of skin and stringers. Three different material configurations have been examined where material data for all configurations have been provided by industrial partners. These configurations are

a) Metallic skin – metallic stringers
b) Composite skin – metallic stringers
c) Composite skin – composite stringers

Two failure criteria were checked during the FE analysis by means of a linear eigenvalue analysis and a static analysis. For post-processing, Python has been used as well. First, five eigenvalues were extracted from the output database. By using five eigenvalues, the effects of discontinuities of mode shifts have been minimized and the optimization solver converged more stably. Second, the maximum strain values (in the case of composite) and maximum von Mises stress (in the case of aluminum) were sought in all iteration points of the skin and stringer nodes. All result values were stored in a text file and fed back to the optimization solver.

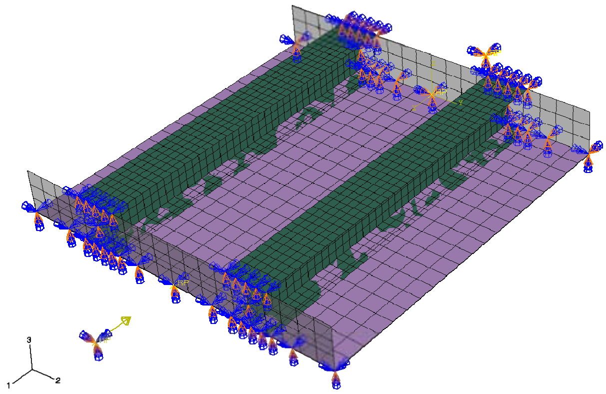


Fig. 3. ABAQUS/CAE model.

2.3 Weight estimation

The structural weight is estimated by a simple piece of Python code; the volume of the current design of the skin/stringer element is calculated and multiplied by the density of carbon/epoxy prepreg (1500 kg/m^3) or aluminum (2700 kg/m^3), respectively. The weight of the total panel is written to a text file.

The quantification of the weight penalty value is difficult and – as mentioned above – dependent on the point of view of the “optimizer”. A first estimation can be made by means of a simple fuel burn calculation.

According to SAS Scandinavian Airlines, an airliner in the A330 class typically consumes about 0.035 l/seat/km with 261 seats and a take-off weight of 233 tonnes. The average flight mass is assumed to be 200 tonnes.

Let us further assume the aircraft flies for 25 years, 250 days/year and a range of 2*8000 km/day, thus estimating the total flown kilometers in the life of the plane at 100 million km. With the above fuel consumption and passenger utilization, the total life fuel consumption yields 914 million liters of kerosene or about 4600 l/kg flight mass. A kerosene price of about € 0.40/l is reasonable [4]. The fuel costs per average flight weight would then result in about € 1840/kg.

The literature shows another image. In 2004, Curran et al. proposed a value of $ 300/kg. Their model, however, considers a depreciation factor of 2 to 5 on the cost side, thus leading to a comparable weight penalty of $ 150/kg to $ 60/kg, or € 112/kg to € 44.8/kg.

The value above and the values of Curran et al. demonstrate the uncertainty of quantifying the weight penalty. They cover a broad spectrum and support the need for a parametric study in which the weight penalty is varied, thus showing the dependency of the optimum solutions with respect to the weight penalty.

2.4 Cost estimation module

Most cost estimation models that are used in aerospace industry can be divided into parametric and feature-based cost models. The first group consists of weight or size based models as proposed by Roskam [5], and Hess et al. [6]. These models, however, could not transfer sufficient variable sensitivity; they were rejected in favor of feature-based cost models.

Semi-empirical feature-based cost models have been studied by Gutowski et al. [7]. They derived first-order velocity models of additive and subtractive processes (e.g. hand lay-up or abrasion operations) for single-curved composite parts.

However, the cost model sought had to be more detailed in order to cover the complexity of manufacturing processes used in the aircraft industry. It had to be adaptable to various composite or non-composite elements, parameterizable by means of variables and run in an automatic mode for the purpose of optimization.

All these features were found in a commercial cost estimating software package, thus keeping the proposed methodology as close to an industrial implementation as possible. This cost estimation tool (SEER-DFM) is developed by Galorath Inc. and is widely used in the aerospace industry; furthermore, it forms the internal cost post-analysis tool of the whole project.

In parallel with the modeling of the structural model, a cost model was built in the graphical user interface of SEER-DFM (see Fig. 4). This model contained all the necessary assumptions and work steps of the manufacturing process. As a second step, the model was exported to a text file, parameterized and prepared for running in command line mode, the so-called server mode.

The cost model of the skin/stringer elements was based on the following assumptions:

1. the composite plate is made out of carbon prepreg, hand lay-up, autoclave cured
2. the metallic stiffeners are conventionally milled from an aluminum block, the latter with constant raw material size
3. the composite stiffeners are made in prepreg by hand-layup
4. the series size is 100 pieces
5. learning curves are not considered.

In a preliminary parametric study, the manufacturing cost of a flat composite panel with varying thickness was investigated. As expected, the cost of the panel performed additively, albeit not continuously. It was found that the steps in cost were a result of the debulking of the prepreg plies. In a second preliminary study, the milling process of a stiffener was parameterized. In this case, the cost performed subtractively to the remaining stiffener volume after the machining process.

The underlying mathematical models of milling and composite manufacturing processes were provided by Galorath. Due to discrete tables and control blocks, the cost formulae are discontinuous and the analytical derivation of gradients was not possible. Therefore, it was decided to consider the algorithms of SEER-DFM as a pure input-output model with the design variables as the input and costs as the output; for the calculation of derivatives, the differential quotient of two solutions would provide gradient information to the solver.

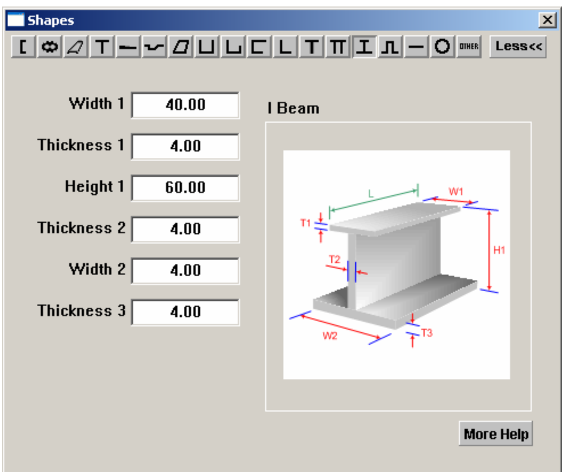


Fig. 4. The definition of the stringer geometry in the graphical user interface of SEER-DFM

2.5 Solver

The problem given in Eq. 2 was transformed to its mathematical formulation given in Eq. 3; the aim of the optimization problem was to find the minimum of the given objective function *f*, subject to prescribed constraint functions g_j.

$$\begin{aligned} &\min_x \quad f(x) \qquad x \in \mathbb{R}^n \\ &\text{subject to } g_j(x) \le 0 \qquad j = 1,\dots,m \\ &\underline{x}_i \le x_i \le \overline{x}_i \qquad i = 1,\dots,n \end{aligned} \tag{3}$$

In this case, $f(x)$ and $g_j(x)$ could not be expressed by explicit formulae, since both objective function and constraints were dependent on the output of two input-output models, the FE model and the cost model. An optimizer was now sought that would (1) incorporate these models, (2) not be too sensitive to disturbances in the form of non-smooth objective and constraint functions, and thus (3) lead to a good convergence rate.

A gradient-based method was chosen for that purpose, i.e. the *method of moving asymptotes* (MMA); see Svanberg [8, 9]. The choice is motivated by

1. the reduced computational workload compared to evolutionary algorithms. For each iteration, the FE problem was solved (n+1) times, whereas an evolutionary algorithm would require an FE calculation for each individual of the population
2. the developmental focus of MMA for structure optimization
3. an existing implementation of MMA in a tool (see Alfgam [10])

In MMA, nonlinear problems are solved through an iterative approach containing inner and outer iterations as displayed in Fig. 5. The approximated subproblem at the kth iteration has the form

$$\begin{aligned} &\min_x \quad \tilde{f}^k(x) \qquad x \in \mathbb{R}^n \\ &\text{subject to } \tilde{g}_j^k(x) \le 0 \qquad j = 1,\dots,m \\ &\underline{x}_i \le x_i \le \overline{x}_i \qquad i = 1,\dots,n \end{aligned} \tag{4}$$

where the basic approximation of the original problem is given as

$$\begin{aligned} \tilde{g}_j^k(x) &= g_j(x^k) \\ &+ \sum_{+,i}^{n} p_{ij}^k \left(\frac{1}{U_i^k - x_i} - \frac{1}{U_i^k - x_i^k} \right) \\ &+ \sum_{-,i}^{n} q_{ij}^k \left(\frac{1}{x_i - L_i^k} - \frac{1}{x_i^k - L_i^k} \right) \end{aligned} \tag{5}$$

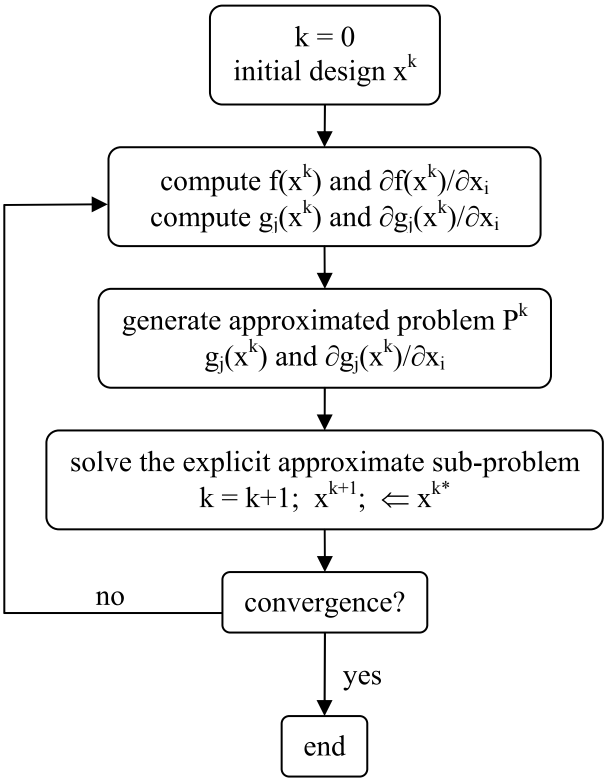


Fig. 5. Iterative scheme of the optimization using the approximation approach

Depending on the sign of the first-order derivative $\partial g_j(x_k)/\partial x_i$ at the current design point, either the lower or the upper asymptote becomes active. This is done by the activation of one of the parameters p_k or q_k while the other remains zero.

$$\begin{aligned} p_{ij}^k &= \max\left\{0,\ (U_i^k - x_i^k)^2 \frac{\partial g_i(x^k)}{\partial x_i}\right\} \\ q_{ij}^k &= \max\left\{0,\ (x_i^k - L_i^k)^2 \frac{\partial g_i(x^k)}{\partial x_i}\right\} \end{aligned} \tag{6}$$

The asymptotes are further updated by the scheme

$$\begin{aligned} L_i^k &= x_i^k - s_i\left(x_i^{k-1} - L_i^{k-1}\right) \\ U_i^k &= x_i^k + s_i\left(U_i^{k-1} - x_i^{k-1}\right) \end{aligned} \tag{7}$$

where parameter s_i is adjusted to narrow or widen the approximation update.

MMA has been implemented in a software tool called Xopt, see [10]. This tool formed the central part of the optimization routine and controlled the execution of the other scripts. As mentioned above, the gradients were calculated as differential quotients from ABAQUS and SEER-DFM.

2.6 Studies performed

The dependency of the design solution on the weight penalty was shown by means of a parametric study, in which the weight penalty was varied from zero to infinity, literally varying from pure cost to pure weight optimization. Finally, the results were associated with the three viewpoints of

a) the supplier: the target weight is determined in advance, whereas the focus is on a pure cost optimization (low weight penalty)

b) the manufacturer: cost and weight are a compromise as discussed in the first section of this article (intermediate weight penalty)

c) the customer: while the cost of the total aircraft is basically defined and governed by politics, each kg weight saving will have an influence on the operating cost of the aircraft; the focus is on a pure weight optimization (high weight penalty)

3 Results

Three material configurations have been optimized as a parameter study with respect to the weight. First, some remarks are made on the behavior of the variables and the cost/weight contribution to the objective function. This is done by means of configuration b) metal/composite. The results of this baseline configuration will be compared with those of configurations a) all-metal and c) all-composite.

3.1. Baseline Configuration in Composite/Metal

In Fig. 6., the variables are shown as a function of the weight penalty. A shift in configuration can be seen at a weight penalty of about € 100-1000/kg. There, the “coarsely stiffened skin” changed to a “densely stiffened skin” configuration. The variables *X1 – X4* were added and plotted as a single curve to facilitate the understanding of the figure.

The layout was mainly 0 deg dominated. For thin skins, however, the above-mentioned rule applied which required a minimum thickness of a prepreg ply for each skin variable; in this case, the layout was rather quasi-isotropic. For thick skins, the layout approached a (70/20/10) distribution, as the 10 % rule limited the amount of 0 deg plies.

From these results, 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 Fig. 7. Cost per unit width and weight per unit width as a function of the weight penalty showed the same transition (see Fig. 8.). It is possible to classify the solution space into three zones:

1. a low-cost solution
2. the transition zone
3. a low-weight solution

The transition zone is even more apparent by plotting the two summands of Eq. 1 separately, as done in Fig. 9. According to these results, state-of-the-art weight optimization was preferable as long as the applied weight penalty is above the transition zone. For weight penalties to the left of the transition zone, costs play a significant role in the design phase; they should not be excluded.

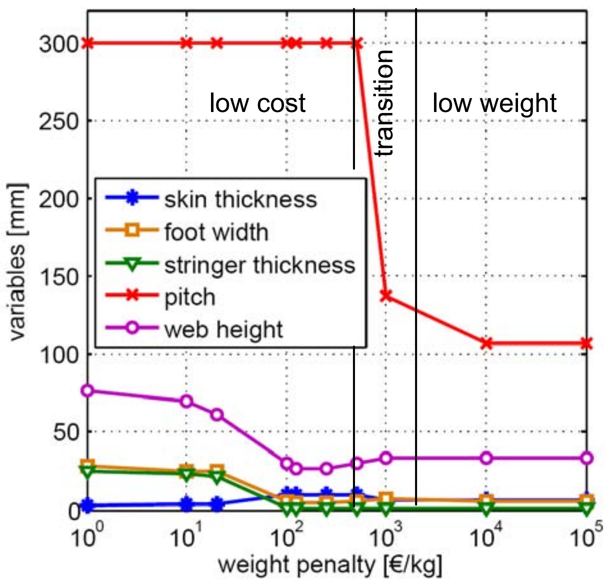
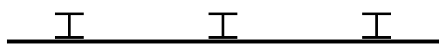


Fig. 6. Variables as a function of the weight penalty for configuration b) metal/composite. *X1-X4* are added and plotted as *skin thickness.*

a) low-cost solution



b) low-weight solution

Fig. 7. Low-cost and low-weight solution.

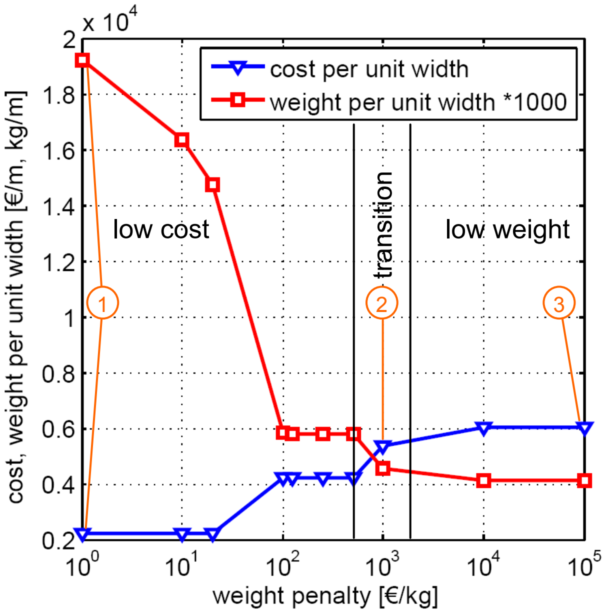


Fig. 8. Cost and weight as a function of the weight penalty. Areas of lowest weight and cost, respectively, are marked.

In Section 2.6 the weight penalties were associated with the viewpoints of suppliers, manufacturers and customers. Here, the impact of these viewpoints is shown in terms of direct operating costs. Therefore, the three design solutions of the optimization were examined by a thought experiment.

The three design solutions, depicted with ①,② and ③ in Fig. 8, represent the design for the supplier's, the manufacturer's and customer's viewpoint (low, middle and high weight penalty, respectively). The objective function (DOC) was now re-examined by allocating the other's weight penalty, thus showing the increase of DOC for each design not performing at the point it was designed for. The results of this comparison are compiled in Table 2, where the optimum designs are emphasized.

Table 2. Direct operating costs per unit width for solution ①,② and ③ (according to Fig. 8.). The optimum designs are emphasized.

DOC [€,%]	$p = 0$	$p = 10^3$	$p = 10^5$
low-cost design ①	**4.39** **100%**	42.80 217%	3844.4 458%
design solution ②	10.71 244%	**19.76** **100%**	916.1 109%
low-weight design ③	12.04 274%	20.31 103%	**838.7** **100%**

The lowest DOC for each design is obtained by the application of the original weight penalty; this is a direct consequence of the optimality condition. Design ①, for example, is a result of a pure cost optimization; the use of a design ② or ③ at $p = 0$ results in 244% or 274% DOC compared to ①.

Most interesting is the difference between designs ② and ③ at a weight penalty of € 10^3/kg, which is reasonable according to the literature. It can be seen that a purely weight optimized design at a weight penalty of € 10^3/kg performs 3% worse than the optimum solution with integrated cost/weight optimization. A purely cost optimized design ① results in 217% DOC compared to design ②.

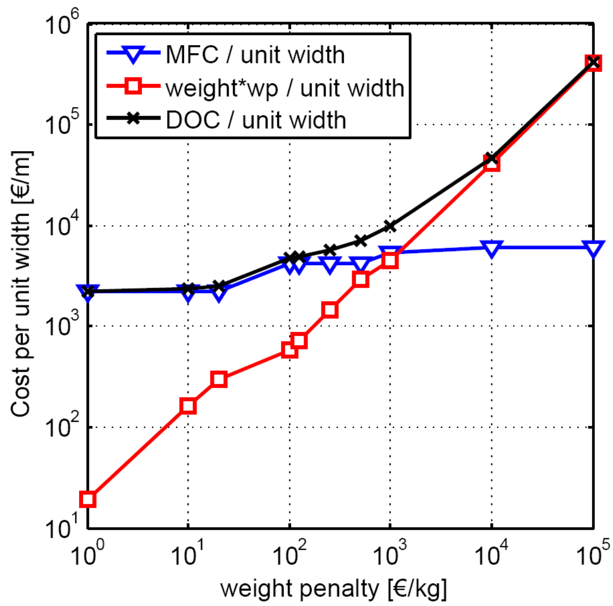


Fig. 9. Cost and weight summands of the objective function as a function of the weight penalty *p*.

3.2. Metal/Metal and Composite/Composite

The results of the all-metal and the all-composite configuration are shown in Fig. 10 and Fig. 11. All three results are congruent with Fig. 6, with the exception of the position of the transition zone; the transition zones are marked in these figures and illustrated in Table 3. Note the way in which the zones are shifted.

Table 3. Transition zones for the three material configurations

configuration	transition zone
a) all-metal	p = € 10-1000/kg
b) composite/metal	p = € 500-2000/kg
c) all-composite	p = € 600-10'000/kg

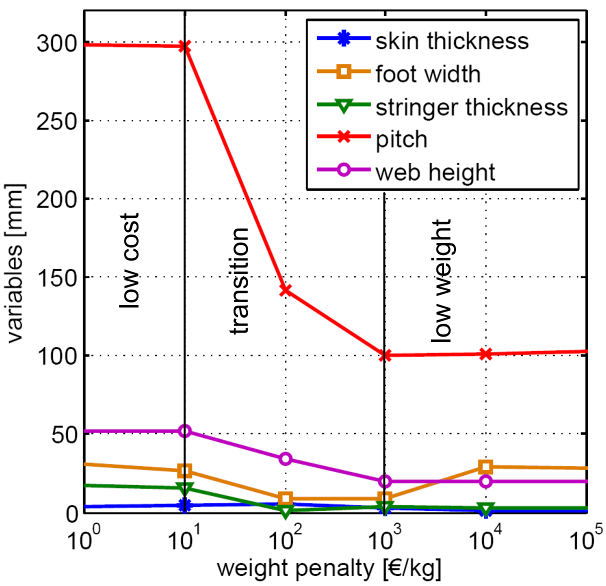


Fig. 10. Variables as a function of the weight penalty for configuration a) metal/metal.

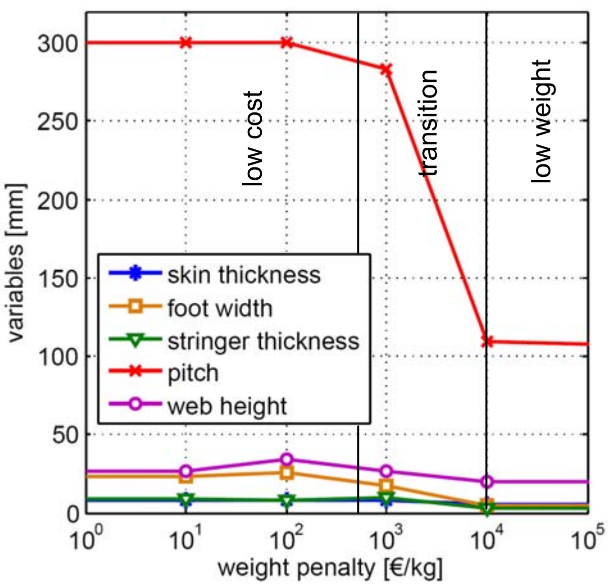


Fig. 11. Variables as a function of the weight penalty for configuration c) composite/composite.

In Fig. 12, the objective functions of all three configurations are plotted. Due to the linear composition of the objective function, the manufacturing cost can be read on the left border of the figure. It can be seen that the manufacturing cost are the lowest for the all-metal configuration, followed by the metal/composite and the all-composite configuration.

It is further interesting to study which material configuration provides the lowest objective function, depending on the weight penalty. For low weight penalties, the all-metal configuration is clearly favorable, thus providing lowest manufacturing costs.

A high weight penalty, on the other hand, leads the choice of material to a mixed material approach. In this case study, an all-composite design did not lead to lower direct operating cost, i.e. the benefits of the weight reduction were not obvious in the investigated spectrum of weight penalties p = € 1-10^5/kg. This is because the weight saving potential of the all-composite configuration has not fully been applied, as the lower geometry limits of the stringer became active.

Note that this selection is based on the chosen element, its input values, and the model accuracy of the performed studies, and should not be generalized. More work has to be done to refine the cost and FE model.

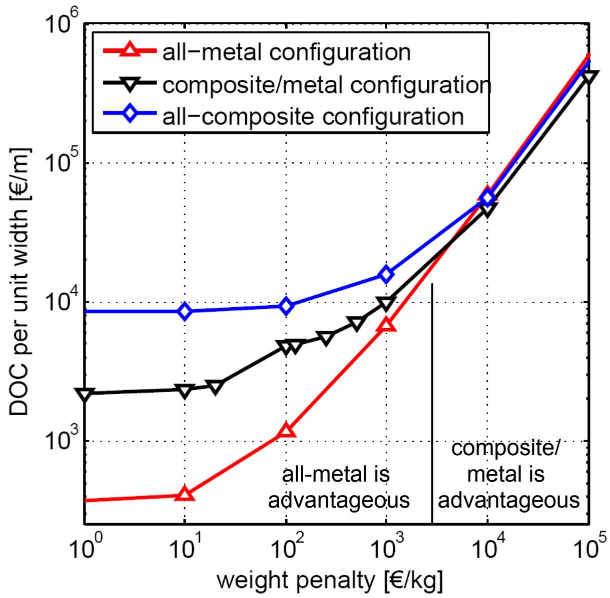


Fig. 12. Cost and weight summands of the objective function for all three material configurations.

4 Conclusion

A methodology for the integrated cost/weight optimization of generic composite elements has been presented. This was done by means of a compressively loaded skin/stringer element. The application of Curran's concept of the weight penalty combined cost and weight of aerospace structures in one objective function. Nevertheless, this concept has to be questioned.

First, the quantification of the weight penalty is difficult. It might depend on the viewpoint of the optimizer, aircraft type and aircraft use. The weight penalty might even depend on what part of the aircraft is investigated; as the weight penalty is a lumped value of the total aircraft, it should be adjusted according to the weight saving potential of the part to be optimized. Nevertheless, the results *were* highly dependent of the weight penalty and certainly showed that the ideal choice of the design solution is 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. The designs were superior for the prescribed weight penalty; re-examining another weight penalty resulted in inferior DOC values as a direct consequence of the optimality conditions. According to the literature, weight penalties of € 100 to 1000 /kg were reasonable; in this range, the need for an integrated cost/weight optimization was a logical conclusion.

Second, the result of the optimization is dependent on the quality of the structural and the cost model. On the structural side, accurate material parameters, boundary conditions and load cases are crucial to obtain correct feedback from ABAQUS. Model errors also occur since the degrees of freedom had to be minimized; thus, reducing computation time while maintaining sufficient accuracy is difficult. On the cost side, accurate cost data is necessary to form the input to SEER-DFM. Expert knowledge is needed, since the manufacturing model has to correspond to the situation in the shop. Consequently, cost models of novel manufacturing processes and methodologies have to be developed (e.g. using SEER's custom calculation feature) and verified *before* being applied to this optimization framework.

Third, it has to be understood that the objective function and the constraints, respectively, are highly non-convex. Local minima solutions could occur, and there is no guarantee that a gradient-based method like MMA would avoid these.

5 Future Work

In the next step, this methodology is applied to the optimization of a real structure, e.g. to a center wing box rear spar of an airliner.

In the stage presented here, the model only captured the cost data for a prescribed set of manufacturing parameters. An investigation showed that – by using adapted cutter diameters for example – the actual cost estimation would be lower in every iteration. It had to be assumed that the design optimization would converge better by using these adapted manufacturing processes. This sub-optimization, however, was not implemented at this stage of the investigation; this is subject to future work.

Last, the proposed MDO scheme will be refined by model enhancements as indicated in Fig. 1. For example, a manufacturing simulation is planned to be implemented to capture producibility constraints (e.g. fiber misalignment due to draping); an other module could include a feature-based model for non-destructive testing cost.

Acknowledgments

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