<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Structural and multidisciplinary optimization (Print)*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Kaufmann, M., Zenkert, D., Wennhage, P. (2010)
Integrated cost/weight optimization of aircraft structures.
Structural and multidisciplinary optimization (Print), 41(2): 325-334
<http://dx.doi.org/10.1007/s00158-009-0413-1>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

The final publication is available at Springer via <http://dx.doi.org/10.1007/s00158-009-0413-1>

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-11339>

Integrated cost/weight optimization of aircraft structures

Markus Kaufmann, Dan Zenkert and Per Wennhage

*Kungliga Tekniska Högskolan (KTH)
10044 Stockholm, Sweden*

July 2007

A methodology for a combined cost/weight optimization of aircraft components is proposed. 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. Hence, the structural engineer can perform the evaluation of a design solution based on economical values rather than pure cost or weight targets. 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. Unlike previous work, the analytical cost and structural models are replaced by commercially available software packages. They allow for a more realistic model of the manufacturing cost, and for arbitrary constraints in the structural analysis. By means of parametric studies it is shown that the design solution strongly depends on the magnitude of the weight penalty.

*Keywords: Cost/Weight Optimization, Operating Cost,
Weight Penalty, Composite Structures*

1 Introduction

The competition between aircraft operators forces the manufacturer to design airliners with lowest possible direct operating cost (DOC). Looking at the drastic rise of the jet fuel price during the last decade, one can understand why a lot of efforts have been undertaken to lower the fuel consumption, which causes a substantial part of the DOC. One strategy to save fuel cost is to lower the structural weight.

The application of carbon fiber reinforced plastics (CFRP) offers great opportunities to lower the structural weight, typically ranging between 10 and 30% compared to an aluminum baseline. The drawback, however, is the increased manufacturing cost. Through cost-effective design, the structural engineers therefore have to find tradeoffs between the minimum weight and the minimum cost solution. Hence, the focus should not only be on pure weight reduction, but rather on a combined minimization of structural weight *and* manufacturing cost.

Early studies on cost aspects in multidisciplinary aircraft design concluded that costs of raw materials, tooling, fabrication, assembly, scrap, repair, certification and environmental factors should be included in the design of composite structures, see Rais-Rohani and Dean [1]. There, the authors identified the risk that the high material, fabrication and tooling costs may make the use of high performance materials cost-ineffective. Sobieszczanski-Sobieski and Haftka motivated a deficit of cost optimization frameworks for composite components by the lack of sophisticated cost models [2], although some costing information has been integrated into the design process, see Geiger and Dilts [3]. The latter presented a conceptual model for an automated design-to-cost approach. The main aim was the provision of a framework that helped the structural engineer in the decision-making process. Heinmuller and Dilts adapted this framework to the aerospace industry. They explained the design-to-cost concept as a tradeoff between operational capability, performance, schedule and cost [4].

At Boeing, an approach for the life-cycle design of aircraft concepts has been developed [5]. Three material configurations for a wing of a high-speed civil transport aircraft were taken into account. It was concluded that lower operating cost could be achieved by a costly design with higher reliability (less maintenance, downtime, etc.), and – vice versa – that the lowest acquisition cost did not always signify the lowest life-cycle cost (LCC). Marx et al. included R&D, manufacturing and sustaining costs, and revenue in their models.

Between 1997 and 1999, Kassapoglou published a series of articles on combined cost/weight optimization. In particular, he presented an approach in which stiffened composite panels were optimized separately for minimum cost C_{min} and minimum weight W_{min} . In a subsequent step, the objective function was redefined including the deviations from both C_{min} and W_{min} in a weighted sum [6–8].

Another study included the manufacturing cost for the multidisciplinary design optimization (MDO) of large civil airliners [9]. The objective function was formed by weight and drag components, and a sub-level cost optimization was implemented in order to achieve the lowest manufacturing cost possible in each iteration. Hence, the cost was subordinated to the weight, while the optimization was accomplished by a topological optimization (number of ribs, number of stiffeners).

At Rolls-Royce, the Design Analysis Tool for Unit-cost Modeling (DATUM) project was launched in 2002. There, the aim was (1) an understanding of the current costing tools available on the market, (2) the development of an own costing tool that would support design decisions throughout the development process and (3) its application to an optimization framework [10].

Park et al. pursued the optimization of structures considering mechanical performance and manufacturing cost. For the design of a resin-transfer-molded part, the stacking sequence of a composite plate was optimized in order to maximize the stiffness. Simultaneously, the mold filling time was minimized by changing the number and position of resin injection gates. A weighted sum approach was used with the displacement and the filling time as the two objectives [11].

Further work in the field of cost optimization was presented in the publication entitled "Shape optimization of heavy load carrying components for structural performance and manufacturing cost" [12]. The authors presented a cost optimization framework that minimized the machining cost of an aluminum torque tube subject to stress constraints. A Sequential Quadratic Programming (SQP) method was chosen for the optimization of six design variables, and the objective function was formed by the material cost, the machining cost and the tooling cost. The machining process was modeled as a virtual machining model in Pro/MFG, where machining times could be extracted once the tool path computation was completed. Neither objective function nor constraints, however, contained a contribution from the part weight.

Kelly, Wang and Dutton resumed the idea of Kassapoglou and proposed an objective function which linked the weight to the cost by a factor \$500/kg, using a weighted sum approach [13,14].

In our study, a methodology for the optimization of aircraft components is proposed that combines the advantages of several approaches mentioned above. In particular the methodology should be

- based on reliable and approved numerical models
- reasonably fast to solve the problem, as it is used in the preliminary phase of aircraft design
- be based on a (for structural engineers) understandable approach of combining manufacturing cost with weight goals.

A straightforward approach for this purpose is the use of a reduced type of direct operating cost (DOC). This DOC combines the manufacturing cost and the weight by the introduction of a weight penalty in a weighted sum. Curran et al. investigated this approach with DOC as the objective function. Their review article gives a broad overview of what has been done within cost estimation [15]. They also described how DOC was simplified for optimization purposes [16]. The quantification of the weight penalty, however, is not simple, as the effect of weight reductions depends on the perspective in which the methodology is used. The 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. The approach of weighted sums has been resumed in the work of Iqbal et al., who applied it on the optimization of a truss structure [17].

In this paper, the methodology is extended to the cost/weight optimization of generic composite elements and exemplified by means of a case study. The minimum cost/weight solution with respect to the analysis with different material properties,

manufacturing techniques and cost allocations is studied. In particular, the solutions of an all-metal, a metal-composite and an all-composite panel are compared.

2 Method

The objective function of the optimization problem was defined as

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

where C_{man} represents the manufacturing cost (in €), p is a weight penalty (in €/kg) and W is the structural weight (in kg) of the element. The optimization routine is illustrated in Figure 1. The modules comprise

1. geometrical setup/design variables
2. FE model
3. weight estimation module
4. cost estimation module
5. solver

These modules are described in the sections below.

Figure 1: The optimization loop.

The optimization problem can be 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 $\underline{x}_i, \bar{x}_i$ as the lower and upper boundaries, respectively. In this study, the methodology was tested on a so-called skin/stringer element.

2.1 The geometrical setup and the 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 were midplane symmetrical with a $[0/90/45/-45]_s$ stacking sequence. This layout is not used in that form in actual aircraft construction, but the advantage is its general usability for optimization purposes and parametrization in the preliminary design phase.

The upper and lower limits of the thickness variables were chosen such that the industrial specifications were maintained. Therefore, one could guarantee that there was at least one ply in each direction (the lower boundary for x_1 to x_4 is 0.26 mm) and that there were at least 10% plies in each direction. The variables of the model are shown in Figure 2 and explained in Table 1.

Figure 2: Variables of the skin/stringer panel. Variables x_1 - x_4 refer to ply thicknesses in $[0/90/45/-45]_s$ direction.

In the case of a *composite stringer*, optimization trials showed that the fiber distribution was clearly 0° dominated. Hence, the laminate generally consisted of 70% fibers in the direction of 0° , 20% in $\pm 45^\circ$ and 10% in 90° . This allowed the use of the total profile thickness as one single variable (x_6) while maintaining the design guidelines that required at least 10% fibers in each ply direction.

Instead of optimizing a panel with a fixed width using a discrete number of stiffeners, the panel was build up with two stiffeners with a continuously varying distance x_7 . The width of the panel was given as twice the stringer pitch. Hence, the objective function was formed by weight per unit width and cost per unit width, respectively. The eight variables and corresponding limits are listed in Table 1. Note that x_3 and x_4 are equal due to symmetry.

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

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 to ABAQUS/CAE and parameterized with the help of Python scripts. Python scripts allowed the creation and modification of the shape

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

Variable	$\underline{x}_i$	$\bar{x}_i$	Description
x_1	0.26	8	0° skin thickness
x_2	0.26	8	90° skin thickness
x_3	0.26	8	45° skin thickness
$x_4 = x_3$	0.26	8	−45° skin thickness
x_5	5	50	stringer width
x_6	1	25	profile thickness
x_7	100	300	stringer pitch
x_8	20	60	stringer height

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 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 [18].

The model was constrained by periodical boundary conditions along the sides and meshed with shell elements of type S4R. The introduction of the compressive loads was 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. This simplification prevented local inter-rivet buckling. The proposed framework, however, could be enhanced by more detailed and elaborated structural models if needed.

Three different material configurations were examined where material data for all configurations were provided by industrial partners. These configurations were

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

The two most likely failure criteria for a skin/stringer panel (such as *buckling* and *compression-after-impact*) were checked during the FE analysis, by means of a linear eigenvalue analysis and a static analysis. For post-processing, Python was used as well. First, five eigenvalues were extracted from the output database. By using five eigenvalues, the effects of discontinuities of mode shifts decreased 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 text files and fed back to the optimization solver.

Note that the chosen test case was representative of a typical problem in aircraft design, and that the geometry, the load case, the material and the failure criteria could easily be altered.

Figure 3: ABAQUS/CAE model.

2.3 Weight estimation

The structural weight was estimated by a simple Python code: the volume of the current design of the skin/stringer element was calculated and multiplied by the densities of carbon/epoxy prepreg (1500 kg/m^3) and aluminum (2700 kg/m^3), respectively.

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

Let us further assume that the aircraft flies for 25 years, 300 days/year and a range of 2.7000 km/day, thus estimating the total flown kilometers in the life of the plane to 100 million km. With the fuel consumption and passenger utilization above, the total life fuel consumption is about 1 billion liters of kerosene or about 5000 l/kg flight mass. A kerosene price of about €0.40/l was reasonable in 2007. The fuel cost per mass unit would then result in €1500/kg to €2000/kg.

The literature shows a different picture. In 2004, Curran et al. proposed a value of \$300/kg. Their model, however, considered 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 (as of April 2007).

The range of our estimations and the values of Curran et al. demonstrated the uncertainty of quantifying the weight penalty, especially when considering that the fuel price rose by a factor 5 between 2002 and 2008. They covered a broad spectrum and supported the need for a parametric study in which the weight penalty was varied, thus showing the dependency of the optimum solutions with respect to the weight penalty.

2.4 Cost estimation

Most cost estimation models that are used in aerospace industry can be divided in parametric and feature-based cost models. The first group consists of weight- or size-based models as proposed by Roskam [19], and Hess et al. [20]. These models, however, could not transfer sufficient variable sensitivity and were rejected in the current study in favor of feature-based cost models.

Semi-empirical feature-based cost models were studied by Gutowski et al. [21]. They derived first-order velocity models of additive and subtractive processes (e.g. hand layup 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 estimation software package, thus keeping the proposed methodology close to an industrial implementation. This cost estimation tool (SEER-MFG) was developed by Galorath Inc. and is widely used in the aerospace industry.

In parallel with the modeling of the structural model, a cost model was built in the graphical user interface of SEER-MFG (see Figure 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 was made of carbon prepreg (hand-laid, autoclave-cured)
2. the metallic stiffeners were conventionally milled from an aluminum bar stock, the latter with constant raw material size
3. the composite stiffeners were made in prepreg (hand-laid, autoclave-cured)
4. the production quantity was 100 units

The first three assumptions were typical for the production of aircraft structures. The production quantity was arbitrary for the methodology itself. It was, however, set to 100 units in order to reduce the influence of the otherwise substantial tooling cost in composite manufacturing and to reflect a mature manufacturing technology. Finally, learning curves were neglected, as they were sensitive to the underlying assumptions and therefore potentially misleading

During the stacking of composite prepregs, the layers are consolidated in regular intervals, typically every fourth ply. This so-called *debulking* causes steps in the cost function, which in turn decrease the convergence. In addition, the milling processes are discontinuous due to discrete tables and control blocks, and the analytical derivation of gradients not possible. Therefore, it was decided to consider the algorithms of SEER-MFG as an input-output model with the design variables as the

input and the cost as the output. For the calculation of derivatives, the difference quotient of two solutions provided gradient information to the solver.

Figure 4: The definition of the stringer geometry in the graphical user interface of SEER-MFG.

2.5 Solver

The problem given in Equation (2) was transformed to its mathematical formulation seen in Equation (3). The aim of the optimization problem was to find the minimum of an objective function f , subject to prescribed constraint functions g_j .

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

In this case, $f(x)$ and $g_j(x)$ were formed by the *DOC* and structural requirements (i.e. safety against buckling, a *von Mises* and a *maximum strain* criterion), respectively. It is again emphasized that the constraints are representatives of a typical problem in aircraft design, and that the setup of the case study could be modified.

Functions $f(x)$ 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 could incorporate 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. A gradient-based method was chosen for that purpose, i.e. the method of moving asymptotes (MMA), see Svanberg [22] and [23]. The choice is motivated by

1. the reduced computational workload compared to evolutionary algorithms. As the methodology was intended to be used in the preliminary design phase, the time to solve the problem was crucial for its applicability.
2. the developmental focus of MMA for structure optimization

MMA had previously been implemented in a software tool called Xopt, see [24]. 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-MFG.

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

1. the supplier: the target weight was determined in advance, whereas the focus was on pure cost optimization (low weight penalty)
2. the manufacturer: cost and weight were a compromise (intermediate weight penalty)
3. the end user: while the price of the total aircraft is basically defined and governed by marketing strategies, each kilogram weight saving has an influence on the operating cost of the aircraft. The focus here was on pure weight optimization (high weight penalty)

3 Results

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

3.1 Baseline configuration in composite-metal

In Figure 5, the variables are shown as functions of the weight penalty. A shift in configuration can be seen at a weight penalty of about €500-2000/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. For very thin skins, however, the above-mentioned rule applied which required a minimum thickness of a prepreg

Figure 5: Variables as a function of the weight penalty for configuration b) metal/composite. x_1 - x_4 are added and plotted as one variable, the skin thickness.

ply for each skin variable. In this case, the layout was quasi-isotropic. For thick skins, the layout approached a (70/20/10) distribution, as the 10% rule limited the amount of 0° plies.

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 6.

Figure 6: Coarsely stiffened low-cost and densely stiffened low-weight solution.

The cost per unit width and the weight per unit width as a function of the weight penalty showed a similar shape (see Figure 7). It is possible to classify the solution space in three zones:

- low-cost solution
- transition zone
- low-weight solution

Figure 7: Cost and weight as a function of the weight penalty. Areas of lowest weight and cost, respectively, are marked.

The transition zone is even more apparent when plotting the two summands of Equation (1) separately, as done in Figure 8. According to these results, state-of-the-art weight optimization is 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 and should thus not be excluded.

Figure 8: Cost and weight summands of the objective function as a function of the weight penalty p .

In Section 2.6 the weight penalties were associated with the viewpoints of suppliers, manufacturers and customers, and the effects of these viewpoints were shown in terms of direct operating cost. 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 Figure 7, represented the designs for the supplier's, the manufacturer's and customer's viewpoint (low, intermediate 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 choosing a "wrong" design solution. The results of this comparison are compiled in Table 2, where the optimum designs are emphasized. The lowest *DOC* for each design was obtained by the application of the original weight penalty, hence the 100%; each column shows the *DOC* of the reallocated design solutions and their percentages for the sake of comparison. Three examples are given here in order to illustrate the effect of solutions not performing as they were designed for.

Table 2: Direct operating cost per unit width for solution 1, 2 and 3 (according to Figure 7). The optimum designs are emphasized.

<i>DOC</i> [€, %]	Part supplier ($p = 0$)	Intermediate design ($p = 10^3$)	End user ($p = 10^5$)
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%

Part supplier low-cost design preferred. Using a low-weight design instead, *DOC* is 2.7 times too high. This scenario is common for a part supplier manufacturing a part that is originally designed for low weight.

Intermediate design optimum with $p = \text{€}1000/\text{kg}$ preferred. Using a low-weight design instead, the *DOC* is 3% too high. This scenario is representative for an aircraft manufacturer who optimizes structures for low weight without including cost in the objective function.

End user low-weight design preferred. Using a low-cost design instead, the *DOC* is 4.5 times too high.

3.2 All-metal and all-composite

The results of the all-metal and the all-composite configuration are shown in Figures 9 and 10. All three results are congruent with Figure 5, with the exception of the position of the transition zones which are marked in the figures and listed in Table 3. Note the way in which the zones are shifted.

Figure 9: Variables as a function of the weight penalty for configuration a) all-metal.

Table 3: Transition zones for the three material configurations

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

In Figure 11, 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 is the lowest for the all-metal configuration, followed by the metal/composite and the all-composite configuration.

The selection of the material system which provides the lowest objective function (as function of the weight penalty) was of particular interest. For low weight penalties, the all-metal configuration was clearly favorable, thus providing lowest manufacturing cost. A high weight penalty led the material selection to a mixed material approach. Here, an all-composite design did not lead to lower direct

Figure 10: Variables as a function of the weight penalty for configuration c) all-composite.

operating cost, as no weight benefits could be seen in the investigated spectrum of weight penalties $p = \text{€}1 - 10^5/\text{kg}$. This was a consequence of the active lower variable limits of the stringers. These active constraints prevented the utilization of the full weight saving potential of the all-composite configuration.

Note that this selection was based on the chosen component, its input values, and the model accuracy of the performed studies, and the results should not be generalized.

4 Conclusions

A methodology for the integrated cost/weight optimization of generic composite elements was presented. This was done by means of a compressively loaded skin/stringer element. The application of Curran's weight penalty combined cost and weight of aerospace structures in one 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. The weight penalty might even depend on what part of the aircraft is investigated since 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.

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. The designs were superior for the

Figure 11: Cost and weight summands of the objective function for all three material configurations.

prescribed weight penalty. The re-examination of another weight penalty resulted in inferior *DOC* values as a consequence of the optimality conditions. According to the literature, weight penalties of €100-1000/kg were reasonable. In this range, there is a need for an integrated cost/weight optimization.

Second, the result of the optimization is dependent on the quality of the structural and the cost models. 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 need to be minimized. Thus, the reduction of computation time while maintaining sufficient accuracy is difficult. On the cost side, accurate cost data is necessary to form the input to SEER-MFG. 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 is understood that the objective function and the constraints 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 adjusted manufacturing parameters. This rather complex sub-optimization of machining and composite manufacturing processes, however, is not implemented at this stage.

Further, a manufacturing simulation is planned to be implemented to capture producibility constraints (e.g. fiber misalignment due to draping). Another module includes a feature-based model for non-destructive testing cost.

6 Acknowledgments

This work is part of the European Framework Program 6, project ALCAS, AIP4-CT-2003-516092. Special thanks go to Alfgam AB for the use of Xopt and to Galorath International for the use of the cost estimation package SEER-MFG.

Bibliography

- [1] M. Rais-Rohani and E. B. Dean. Toward manufacturing and cost considerations in multidisciplinary aircraft design. In *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, volume 4, pages 2602–2612, 1996.
- [2] J. Sobieszczanski-Sobieski and R. T. Haftka. Multidisciplinary aerospace design optimization: survey of recent developments. *Structural and Multidisciplinary Optimization*, 14:1–23, 1997.
- [3] T. S. Geiger and D. M. Dilts. Automated design-to-cost: Integrating costing into the design decision. *Computer Aided Design*, 28(6-7):423–438, 1996.
- [4] B. Heinmuller and D. M. Dilts. Automated design-to-cost: Application in the aerospace industry. In *Proceedings - Annual Meeting of the Decision Sciences Institute*, volume 3, pages 1227–1229, 1997.
- [5] W. J. Marx, D. N. Mavris, and D. P. Schrage. A knowledge-based system integrated with numerical analysis tools for aircraft life-cycle design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 12:211–229, 1998.
- [6] C. Kassapoglou. Simultaneous cost and weight minimization of composite-stiffened panels under compression and shear. *Composites Part A: Applied Science and Manufacturing*, 28(5):419–435, 1997.
- [7] C. Kassapoglou. Minimum cost and weight design of fuselage frames. part a: Design constraints and manufacturing process characteristics. *Composites Part A: Applied Science and Manufacturing*, 30(7):887–894, 1999.
- [8] C. Kassapoglou. Minimum cost and weight design of fuselage frames. part b: Cost considerations, optimization, and results. *Composites Part A: Applied Science and Manufacturing*, 30(7):895–904, 1999.

- [9] K. Gantois and A. J. Morris. The multi-disciplinary design of a large-scale civil aircraft wing taking account of manufacturing costs. *Structural and Multidisciplinary Optimization*, 28:31–46, 2004.
- [10] J. Scanlan, A. Rao, C. Bru, P. Hale, and R. Marsh. Datum project: Cost estimating environment for support of aerospace design decision making. *Journal of Aircraft*, 43(4):1022–1028, 2006.
- [11] C. H. Park, W. I. Lee, and A. Vautrin. Simultaneous optimization of composite structures considering mechanical performance and manufacturing cost. *Composite Structures*, 65(1):117–127, 2004.
- [12] M. S. Edke and K. H. Chang. Shape optimization of heavy load carrying components for structural performance and manufacturing cost. *Structural and Multidisciplinary Optimization*, 31(5):344–354, 2006.
- [13] K. Wang, D. Kelly, and S. Dutton. Multi-objective optimisation of composite aerospace structures. *Composite Structures*, 57(1):141–148, 2002.
- [14] D. Kelly, K. Wang, and S. Dutton. A guided tradeoff for cost and weight for generating optimal conceptual designs. In *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, volume 2, pages 894–904, 2003.
- [15] R. Curran, S. Raghunathan, and M. Price. Review of aerospace engineering cost modelling: The genetic causal approach. *Progress in Aerospace Sciences*, 40(8):487–534, 2004.
- [16] R. Curran, A. Rothwell, and S. Castagne. A numerical method for cost-weight optimisation of stringer-skin panels. In *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, volume 7, pages 5262–5277, 2004.
- [17] A. Iqbal and J. S. Hansen. Cost-based, integrated design optimization. *Structural and Multidisciplinary Optimization*, 32(6):447–461, 2006.
- [18] ABAQUS. *Online Documentation*. ABAQUS, Inc., March 2006. Version 6.6-1.
- [19] J. Roskam. *Airplane Design Part VIII: Airplane Cost Estimation Design Development and Manufacturing and Operating*. Darcorporation, 1990.
- [20] R. W. Hess and H. P. Romanoff. *Aircraft Airframe Cost Estimating Relationships: All Mission Types*. RAND Corporation, 1987.
- [21] T. Gutowski, D. Hoult, G. Dillon, E.-T. Neoh, S. Muter, E. Kim, and M. Tse. Development of a theoretical cost model for advanced composite fabrication. *Composites Manufacturing*, 5(4):231–239, 1994.
- [22] K. Svanberg. Method of moving asymptotes – a new method for structural optimization. *Journal for Numerical Methods in Engineering*, 24(2):359–373, 1987.
- [23] K. Svanberg. A globally convergent version of MMA without linesearch. In *Proceedings of the First World Congress of Structural and Multidisciplinary Optimization, Goslar (Germany)*, pages 9–16, May/June 1995.
- [24] Xopt. *Optimeringsprogrammet Xopt - Manual*. Alfgam Optimering AB, 2.0 edition, October 2001.