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# Cost optimization of composite aircraft structures including variable laminate qualities

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## 1 Abstract

2 Composite structures can lower the weight of an airliner significantly. The increased  
3 production cost, however, requires the application of cost-effective design strategies  
4 in which cost, weight and the desired laminate quality are taken into account. This  
5 paper proposes an optimization framework for composite aircraft structures that  
6 minimizes the direct operating cost on a part level. In addition to previous models,  
7 a non-destructive testing model is implemented that calculates design allowables  
8 of a laminate based on the ultrasonic scan parameters. In a case study, the effect  
9 of the laminate quality on the direct operating cost is discussed. It is investigated  
10 how the flaw size and therefore the scan pitch of a composite laminate can influence  
11 the optimal solution in terms of cost and weight; thus, the manufacturing cost, the  
12 non-destructive testing cost and the weight of a component can be balanced by  
13 optimizing the laminate quality in an early design phase.

*Key words:* A. Structural Composites, D. Non-destructive testing, B. Strength, C. Finite element analysis (FEA), Optimization

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## 14 1 Introduction

15 Today's performance requirements necessitate the full application of carbon fibers to  
16 primary structures of airliners. The shift to composite materials lowers the structural  
17 weight significantly; the drawback, however, is the increased manufacturing cost.

18 Through cost-effective design, tradeoffs between the minimum weight and the minimum

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19 cost solution are found, two extremes that often contradict each other. Weight savings  
20 are directly associated with a reduced fuel consumption and an increased payload, while  
21 the reduced manufacturing cost has an impact on the acquisition cost. Therefore, the  
22 focus should not only be on pure weight reduction, but rather on a combined  
23 minimization of manufacturing cost *and* structural weight.

24 Attempts for a combined cost/weight optimization have been done by Geiger and Dilts  
25 [1], Heinmuller and Dilts [2], Kassapoglou [3–5], Marx et al. [6], Gantois [7], the  
26 Rolls-Royce's DATUM project [8], Park et al. [9], Edke and Chang [10], and Curran et  
27 al. [11]. Further, Kelly and Wang [12], Wang et al. [13], Curran et al. [14], and Kaufmann  
28 et al. [15] incorporated the idea of a *weight penalty*; this weight penalty was applied to  
29 balance the tradeoff between manufacturing cost and structural weight. Each kilogram  
30 of structural weight was given a lifetime fuel burn cost and the sum of fuel burn cost  
31 and manufacturing cost formed the objective function. Apart from embedding cost and  
32 weight, not much research has been performed on optimizing aircraft structures for  
33 life-cycle cost (LCC) or direct operating cost (DOC), as defined by Roskam [16].  
34 Further, no attempts have been done to include the material quality of composite  
35 laminates into these optimization frameworks.

36 In the studies cited above it is assumed that the quality of the raw material is equal and  
37 no isolated inspection cost were identified in the cost models. This is due to the fact  
38 that the models have been built up for metallic structures, where in-service inspection  
39 plays a minor role in the design process or that the cost model was not detailed enough  
40 to capture these costs. Unlike their metallic counterparts, however, composite parts are  
41 fabricated *in-situ* and the quality of these structures is highly dependent on the process  
42 robustness and the workmen skills. As a result, every composite part has to undergo  
43 rigorous ultrasonic testing. Here, non-destructive testing (NDT) currently is the key to  
44 maintain the quality assurance of the structure. Typical manufacturing generated  
45 defects in composite parts are voids, porosity, fiber misalignment, wrinkling, poor cure,  
46 resin-rich or resin-poor areas and the inclusion of foreign bodies.

47 Both the manufacturing of autoclave prepreg parts and the NDT methods have  
48 continuously been developed and refined during the last years. Nevertheless, the design  
49 is still based on rather conservative presuppositions, such as two percent  
50 through-the-thickness porosity and flaws of a size of typically 6mm in diameter. In this  
51 work, these presuppositions are challenged. In particular, the optimization framework  
52 developed in [15] has been enhanced by an NDT cost and strength reduction model.

53 The first time NDT cost has been mentioned in the literature was in 1937 by Schmid  
54 [17]. Schmid investigated the cost of x-ray, gamma and magnetic testing of metal parts  
55 in terms of recurrent and non-recurrent cost. Although the test methods and  
56 components were not related to aircraft structures, this article is noteworthy. Schmid  
57 pointed out that the choice of an appropriate testing method has to be in proportion to  
58 its cost, the cost of the structural part and the cost of possible flaws and damages.  
59 Depending on the complexity of the part, different technical skills were needed, thus  
60 leading to different labor cost. Simple, similar components, for example, need a less  
61 qualified operator than complex, forged components. The cost was further determined  
62 by the inspection method, the part size and the accuracy in flaw detection.

63 Since then, most of the relevant literature concentrated on the cost of aircraft  
64 maintenance and not on *in-production* testing. For instance, the life-cycle cost of  
65 aircrafts under the consideration of NDT was addressed by Hagemaiier in [18,19].  
66 Another example is shown by Kale [20] who combined the weight optimization of an  
67 aluminum panel with a reliability based model of the periodic in-service inspection.

68 In this work, an cost/weight optimization framework is proposed that incorporates  
69 manufacturing cost, inspection cost and the weight of the component. In addition to  
70 previous studies, the NDT cost are calculated separately by means of a feature-based  
71 cost estimation model. Moreover, the laminate quality is considered as a design variable;  
72 this variable has a distinct influence on the scan parameters and therefore the scan cost,  
73 and it controls the strength prediction of the laminate.

74 **2 Method**

75 The optimization framework herein consists of the necessary routines to calculate the  
 76 objective function and the constraints. In the following these blocks are described in  
 77 detail.

78 *2.1 Optimization framework*

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

$$\begin{aligned}
 & \min && DOC \text{ of a composite element} \\
 & \text{subject to} && \text{structural requirements} \\
 & && \underline{x}_i < x_i < \bar{x}_i, \quad i = 1 \dots n
 \end{aligned} \tag{1}$$

81 where  $x_i$  are the design variables and  $\underline{x}_i$  and  $\bar{x}_i$  the corresponding lower and upper  
 82 limits. Examples of variables are laminate thicknesses, the distance between two  
 83 adjacent stiffeners, the height and width of the stiffeners or the laminate quality.

84 The objective function of the optimization problem is formed by a simplified version of  
 85 the direct operating cost  $DOC$ . Here, the  $DOC$  is formed by the weighted sum

$$DOC = \alpha_1 C_{man} + \alpha_2 C_{ndt,prod} + \alpha_3 N C_{ndt,serv} + pW \tag{2}$$

86 where  $C_{man}$  is the manufacturing cost,  $C_{ndt,prod}$  is the cost for non-destructive  
 87 in-production testing,  $C_{ndt,serv}$  is the cost of a single in-service inspection,  $p$  is a weight  
 88 penalty (given as the lifetime fuel burn cost per weight) and  $W$  is the weight of the  
 89 structure. The parameters  $\alpha_i$  incorporate calibration factors due to depreciation,  
 90 overhead cost and other cost adjustments, and  $N$  is the number of regular inspections

91 during the lifetime of the aircraft. In a first step this number is a constant, in future this  
92 value could be based on the location, the stress level and the exposure of the part.

93 In Fig. 1, the optimization routine is illustrated, including an analysis block containing  
94 an FE model, a manufacturing cost model, a weight model and an NDT model.

## 95 *2.2 FE Analysis*

96 The FE evaluation is done in ABAQUS/Standard and comprises a linear buckling  
97 analysis and the computation of a composite failure criterion. It is important to note  
98 that the results and conclusions presented here are specific to the flaw type and size  
99 included in the analysis and the failure modes assumed (buckling and maximum strain  
100 failure) and cannot be generalized before other failure modes (e.g. crippling, local  
101 buckling of a delamination, impact damage) are accounted for. Hence, the structural  
102 constraints used herein are only examples of possible criteria; the modular design of the  
103 optimization framework allows also the implementation of a more advanced analysis.

104 The FE model has been parameterized in terms of variables, shown as  $x_i$  in Equation  
105 (1). Changes in the variables result in a new set of buckling eigenvalues or maximum  
106 strain numbers; these form the structural constraints to the optimization problem and  
107 have to be fulfilled in order to provide a feasible solution. All changes in the ABAQUS  
108 model are done by means of Python scripts.

## 109 *2.3 Manufacturing Cost*

110 During the manufacturing of composites, several operations and processes can be related  
111 to costs. Examples are the stacking of prepreg plies, debulking, consumables, curing or  
112 tooling. Each process represents a time need and the material cost. Time needs can be  
113 translated into labor costs; the sum of all cost plus an overhead represents the total cost  
114 to manufacture the panel. This kind of feature-based model (see Niazi et al. [21]) is  
115 easily parameterizable, as features can be added, removed or modified. The

116 commercially available cost estimation software SEER-DFM<sup>1</sup> incorporates all these  
117 capabilities and is used therefore. Similar to the approach done for the FE calculation,  
118 an initial model has to be built up in the graphical user interface of the software. This  
119 model contains all the necessary assumptions and work steps of the manufacturing  
120 process; it is exported to a text file, parameterized in terms of variables  $x_i$  and prepared  
121 for running in command line mode, the so-called server mode.

#### 122 2.4 Weight estimation

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

#### 126 2.5 Non-Destructive Testing

127 Unlike the estimation of the manufacturing cost, it was decided to develop an in-house  
128 feature-based tool for the evaluation of the non-destructive testing cost. It contains the  
129 estimation of the NDT cost for in-production and in-service testing, and the adjustment  
130 of the material strength.

131 Some preconditions that apply to the manufacturing of composite aircraft structures can  
132 be assumed. For example, *all* components are *thoroughly* tested before the assembly,  
133 which includes that the total surface of each structural member is scanned. Testing is  
134 performed on condition of series production, i.e. the testing process is cost optimal in  
135 terms of operator level and test equipment and no non-recurring costs (such as the  
136 purchase of probes or other equipment) are incorporated. No reject rate has been  
137 implemented; the development of a reliability-based cost model will be developed in a  
138 later stage.

139 In the case of NDT, the generic database provides the following features:

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<sup>1</sup> see Galorath Inc. at <http://www.galorath.com>



- 140 • Thin flat laminate with access from both sides
- 141 • Thin flat laminate with access from one side
- 142 • Thick flat laminate with access from both sides
- 143 • Thick flat laminate with access from one side
- 144 • Radius
- 145 • Adhesive bond

146 Each of these features requires input data in form of the length  $l_k$ , the width  $w_k$ , the  
 147 thickness  $t_k$  and – in case of radii – the radius  $r_k$ , see Fig. 2. On the other hand, the  
 148 feature definition includes a scanning technique, a complexity index, the educational  
 149 level of the operator and associated with the latter a cost per hour or per scanned area.

150 For rectangular scans of plates, flanges and adhesive bonds, the NDT cost of the  $k^{th}$   
 151 feature is calculated as

$$C_{ndt,k} = \frac{l_k w_k}{v_k d_k} \cdot [C_{\text{machine},k} + C_{\text{operator},k}] \quad (3)$$

152 where  $v_k$  is the scan speed and  $d_k$  is the scan pitch (distance between two scan paths) of  
 153 the feature  $k$ . The parameters  $C_{\text{machine},k}$  and  $C_{\text{operator},k}$  represent the hourly rate of the  
 154 test equipment and the operator, respectively.

155 For linear scans of radii, the NDT cost is calculated as

$$C_{ndt,k} = \frac{l_k}{v_k} \cdot [C_{\text{machine},k} + C_{\text{operator},k}] \quad (4)$$

156 and the total cost of non-destructive testing is the sum of all features

$$C_{ndt} = \sum_{k=1}^N C_{ndt,k} \quad N = \text{Number of features.} \quad (5)$$

157 Apart from the scanning cost per area, one has to consider a dependency of the cost on  
 158 the laminate thickness. Several approaches of how to tackle this problem have been  
 159 examined. Finally, it has been decided to introduce the very flexible method of adjusting

160 the structural allowable due to the higher risk of porosity or flaws in thicker structures.  
 161 Hence, a relationship between testing cost and weight is found through the quality of  
 162 the laminate. The following two reductions of the material strength are evaluated.

- 163 • Strength  $\hat{\sigma}_{p,k}$  due to possible porosity; a function of the thickness and the material of  
 164 the cross-section.
- 165 • Strength  $\hat{\sigma}_{f,k}$  due to possible flaws or foreign bodies; a function of the scan pitch, the  
 166 thickness, the material properties (based on coupon tests) and the NDT equipment.

167 Note that all strengths are calculated feature-wise and the strength that is applied in  
 168 the FE calculation is the minimum of each  $\hat{\sigma}_{p,k}$  or  $\hat{\sigma}_{f,k}$ . Both mechanisms are described  
 169 below.

## 170 *2.6 Strength reduction due to porosity*

171 In the design of composite structures, a certain level of porosity is tolerated and  
 172 included in the calculation of the structural performance. Typically, a level of two  
 173 volume percents is stated, a level that has been kept constant during the last two  
 174 decades. With regard to new material systems, optimized manufacturing methods and  
 175 more accurate NDT techniques, this porosity level is about to be challenged.

176 A lot of work has been done to investigate the effect of the laminate thickness and the  
 177 laminate porosity on the mechanical properties, see [22–27]. It has been concluded that  
 178 there exists an exponential degradation of the compressive strength  $\hat{\sigma}_c$ , although this  
 179 decline does not appear as distinctive as for the interlaminar shear strength  $\hat{\tau}$ . In the  
 180 context of isotropic materials, the equation

$$\hat{\sigma} = \hat{\sigma}_{max} e^{Bv_p} \quad (6)$$

181 has elevated to describe this behavior; here,  $\hat{\sigma}_{max}$  is the strength at zero porosity,  $v_p$  is  
 182 the volume fraction of porosity and  $B$  is an empirical constant that depends on  
 183 orientation, shape and size of the pores.

184 As the proposed method is a part of the design process, the laminate thickness  $t$  has to  
 185 be passed into an anticipated porosity level  $v_p$  for a given material and manufacturing  
 186 technique. Lee and Soutis [26] performed a study on the void content with respect to the  
 187 thickness of the specimen and concluded that this value is highly dependent on the  
 188 stacking sequence of the laminate.

### 189 2.7 Strength reduction due to foreign bodies

190 All manufactured composite parts have to be tested for the inclusion of foreign bodies  
 191 (e.g. parts of the release paper of the prepreg) or other delaminations. Nowadays, the  
 192 composite manufacturer defines a minimum flaw size that has to be detected, typically  
 193 being around 6mm in diameter.

194 The probability of detection never reaches 100%. Instead, a stochastic value based on  
 195 the material, the NDT method and the thickness of the material is assumed; quoted  
 196 levels are 90% or 95%, see [28]. According to Huang et al., typical stochastic models  
 197 used are the Gamma distribution or the two-parameter Weibull distribution, see [29].  
 198 For the Weibull distribution, the cumulative distribution function of the probability of  
 199 detection (POD) is given as

$$POD = 1 - e^{-(f/\lambda)^k} \quad (7)$$

200 where  $f$  is the flaw size, and  $\lambda$  and  $k$  are the two shape parameters. A typical curve plot  
 201 for different settings of  $\lambda$  is shown in Fig. 3.

202 As can be seen in this figure, the  $POD$  is higher for thinner laminates (the actual value  
 203 depends on the material, the stacking sequence and the NDT method) and for larger  
 204 flaw diameters. Today's 6mm flaw diameter would require a scan pitch  $d_k$  of  
 205 approximately 2mm, the latter having a direct influence on the NDT costs. By varying  
 206 the maximum flaw size, the quality of the laminate becomes a design variable and the  
 207 material strength experiences an according modification.

208 Different ways to relate the strength to the flaw size exist. Here, open hole compression

209 is proposed, as it represents the most conservative strength reduction for a flaw of a  
210 certain size. For examples on the strength reduction of notched laminates, see Soutis et  
211 al. [30]. Other options could include a separate strength prediction model in FE (e.g. the  
212 simulation of a CAI coupon test) which takes into account the actual stacking sequence  
213 and the flaw size of the section, or the implementation of local delamination buckling as  
214 a function of the flaw size and the through-the-thickness location of the flaw.

215 The variable quality level can be explained as follows: Let us assume that an allowed flaw  
216 diameter  $f$  of *less* than 6mm is applied to a laminate. All flaws that are bigger than  $f$   
217 will be detected, thus causing the part to be rejected. In this case, the (cost) optimum is  
218 found as the tradeoff between the higher NDT cost on one side and the lower structural  
219 weight and manufacturing cost due to higher strength on the other side. On the other  
220 hand, a flaw diameter  $f$  of *more* than 6mm would lead to lower NDT cost, a higher  
221 structural weight and higher manufacturing cost due to the additional plies needed.

222 The resulting algorithm is shown in Fig. 4. It can be seen that the thickness  $t$  and the  
223 maximum allowed flaw size  $f$  form the inputs to the NDT module. In the first step, the  
224 scan pitch  $d_k$  is adapted until a desired probability of detection is met. The direct cost  
225 for non-destructive testing  $C_{ndt}$  is a function of the scanned area (length  $l$  and width  $w$ )  
226 and the scan pitch  $d_k$ . Simultaneously, the strength reduction is calculated and fed into  
227 the FE module where the constraints for the optimization are computed.

## 228 2.8 Solver

229 Based on the results of the analysis, the objective function and the optimization  
230 constraints are evaluated. Then the solver calculates adjusted variables and triggers the  
231 execution of the next iteration. For that purpose, a solver was sought that would  
232 incorporate the analysis blocks in the form of *input-output* models, not be too sensitive  
233 to disturbances in the form of non-smooth objective and constraint functions, and thus  
234 lead to a good convergence rate. In order to minimize the number of FE evaluations, the  
235 method of moving asymptotes (MMA) has been chosen, see Svanberg [31,32]. One can

236 see in the case study below that the parametrization of the design variables as  
237 continuous variables is a rough simplification which accommodates the use of this  
238 gradient-based method.

239 In reality, the thickness is not a continuous variable and it is possible that a  
240 gradient-based method will miss some designs that may be more efficient than the ones  
241 obtained from a gradient-based optimization. Hence, the results from the present study  
242 are viewed as representative of the trends and relative differences of alternate designs  
243 but may not point to the "best" solution.

### 244 3 Case Study

245 In a case study, a generic skin/stringer element has been optimized in order to show the  
246 influence of the NDT cost and the quality level on the overall design. The panel (seen in  
247 Fig. 5) consists of a laminated composite skin and two I-shaped stiffeners that are  
248 adhesively bonded to the skin. As can be seen the skin/stringer element is  
249 parameterized in terms continuous variables, such as the stringer pitch, the panel  
250 thickness, the profile thickness, the web height and the flange width. The discrete  
251 stacking sequence  $[0_m/90_n/\pm 45_p]_s$  has been simplified to a  $[0/90/\pm 45]_s$  layup  
252 with continuous thickness variables. Note that the laminate generally consists of a 70%  
253 fibers in the direction of 0 degree, 20% in  $\pm 45$  degrees and 10% in 90 degrees. This  
254 allows the application of one single variable while maintaining the design guidelines that  
255 require at least 10% fibers in each ply direction. Here, it is again emphasized on the fact  
256 that the chosen test case is representative for a typical problem in aircraft design, and  
257 that the geometry, the load case, the material and the failure criteria could easily be  
258 exchanged. Moreover, further optimization is possible by allowing the stacking sequence  
259 to change. This can lead to more efficient load distribution among skin and stiffeners  
260 and result in lower weight and cost configurations.

261 For the sake of simplicity, it has been chosen to neglect any depreciation factors and

262 cost adjustments (i.e.  $\alpha_1 = \alpha_2 = \alpha_3 = 1$ ) and apply the same equipment and operator  
 263 rates for in-production and in-service inspection. The prescribed probability of detection  
 264 has been set to 95%.

265 Here, five regular inspections during the lifetime of the aircraft have been assumed.

266 Therefore, the objective function results in

$$DOC = C_{man} + C_{ndt,prod} + 5C_{ndt,serv} + pW \quad (8)$$

267 The attention is drawn to the quantification of the weight penalty. One can imagine that  
 268 the cost/weight tradeoff is dependent on factors such as *accumulated flight distance*  
 269 *during aircraft life, engine specific fuel burn, thrust level during flights, environmental*  
 270 *impact penalties* or *fuel price*. Note that an objective determination of  $p$  is difficult, as it  
 271 may vary from customer to customer, the application (civil, cargo, military version of  
 272 the same plane), whether it is optimized for additional payload, fuel saving or additional  
 273 passengers and the way the customer evaluates his product. The literature proposes a  
 274 weight penalty between €45/kg and €380/kg. Own research based on the fuel  
 275 consumption of an airliner in the A330 class and today's fuel price, however, reveals a  
 276 different picture. In this case, the weight penalty  
 277  $p = \text{lifetime fuel burn cost/kg aircraft mass}$  would then result in about €1840/kg. The  
 278 mass reduction of one kilogram might involve a reduction of the gross weight that is  
 279 significantly higher, as the weight of engines and systems can be lowered. And when  
 280 taking the revenue of an additional passenger into account, this value could be one order  
 281 of magnitude higher. Nevertheless, it has been decided to apply a value of €1500/kg to  
 282 the case study in order to accommodate both values from the literature and our own  
 283 calculations.

284 The FE model has been built up in ABAQUS/CAE according to the drawing in Fig. 5.  
 285 It is constrained by periodical boundaries along the sides and meshed with shell  
 286 elements of the type S4R. The introduction of the compressive load has been realized by  
 287 two rigid bodies, simulating the adjacent frame structure. The adhesive bonds have been

288 approximated by tie constraints, thus preventing any separation of skin and stringers.  
 289 Two failure criteria were checked during the FE analysis. First, the maximum strain  
 290 values (MSTRN) were sought in all integration points of the skin and stringer nodes,  
 291 and second, the eigenvalues of a linear perturbation analysis is calculated. Both are fed  
 292 back to the optimization solver. Rather high loads have been applied to this structure  
 293 (2.5 kN per mm width) in order to obtain comparable failure loads for buckling and  
 294 strain; as can be seen below, the model will consist of rather short and stubby stiffeners.  
 295 The maximum strain criterion has been set to 0.005, -0.004 and 0.008 for tension,  
 296 compression and shear, respectively.

297 Referring to the description of the NDT model above, the structure is divided into  
 298 features, such as the skin laminate, further two stringers with two flange laminates, one  
 299 web laminate and four radii each; the two adhesive bonds between skin and stringer are  
 300 two other features.

301 The adjustment of the allowables due to porosity is estimated according to Equation  
 302 (6). The value of  $B = -3.14$  has been adopted from Uhl et al. [23] who performed a  
 303 number of test series for a 16 ply quasi-isotropic carbon/epoxy laminate. The void  
 304 content  $v_p$  as a function of the thickness is required as an input for the equation above.  
 305 The approximate function  $v_p = 0.0025t$  has been extracted from the figures presented by  
 306 Lee and Soutis [26]; in their work they studied the void content with respect to the  
 307 thickness of the specimen. In this first attempt, the strength due to flaws of a given size  
 308  $f$  is based on the work done by Soutis et al. [30], from which the value of  
 309  $\hat{\sigma}_f(f) = \hat{\sigma}_0(-\frac{12.4}{444}(f - 6) + 1)$  has been extracted. Here,  $\hat{\sigma}_0$  refers to the strength of a  
 310 coupon test with 6mm hole size.

311 First, a panel has been optimized for a series of weight penalties, thus resulting in a  
 312 parameter study covering the whole range from pure cost optimization ( $p = 0$ ) to pure  
 313 weight optimization ( $p = \infty$ ). Therefrom, three configurations have been chosen: A  
 314 low-cost panel (a), a cost/weight optimized panel with a fuel penalty of €1500/kg (b),  
 315 and a low-weight panel (c). All three baselines have been obtained without the novel

316 NDT tool presented in this paper.

317 Finally, the behavior of each configuration is investigated when varying the quality level  
318 and laminate thicknesses while the geometry is kept constant. Further the influence of  
319 the probability of detection  $POD$  on the direct operating cost is examined.

## 320 4 Results and Discussion

321 The first part of this section refers to a parameter study done without the activation of  
322 the NDT model. Hence, the results are obtained by optimizing a skin/stringer element  
323 with an objective function given as  $DOC = C_{man} + pW$  and the weight penalty  $p$   
324 varying between 0 and infinity. The results are shown in Fig. 6.

325 A distinctive change in configuration can be seen at a weight penalty of  
326 €1000-10'000/kg. To the left of this change, a low-cost solution is preferable. There, the  
327 skin/stringer panel consists of a thick skin and bulky stiffeners with maximum pitch – as  
328 fewer stringers are used in the low-cost solution, manufacturing costs can be saved in  
329 spite of the higher cost per stiffener. Further, the buckling constraint but not the  
330 maximum strain constraint is active. Hence, the structure is not performing optimally,  
331 and some more cost saving could be possible by enlarging the design space. To the right,  
332 the low-weight configuration comprises a densely stiffened, thin skin with rather fine  
333 stringers and both the structural constraints are active. Three design solutions have now  
334 been chosen as the starting point for the subsequent investigation, see Table 1.

335 Properties marked with asterisks are kept constant in the subsequent investigation.

### 336 *Quality optimization of the low-cost panel ( $p = \text{€0/kg}$ )*

337 First, the cost optimized panel with a stringer pitch of 300mm has been investigated.  
338 This panel has been optimized for a series of flaw sizes, varying from 2 to 20mm. The  
339 results of this study are compiled in Table 2, where a flaw size of 6mm represents the  
340 baseline.



341 As can be seen, the variation of the laminate quality has a considerable impact on the  
342 objective function  $DOC$ . At a flaw size of 2mm, the laminates have to be scanned much  
343 tighter in order to guarantee a probability of detection of 95%. The result is an NDT  
344 cost that is 2.74 times the baseline and a  $DOC$  that is 46% higher than the baseline. It  
345 also can be seen that only the buckling constraint is active for small flaw sizes. As the  
346 buckling load is independent of the strength of the material, it is evident that no weight  
347 reduction is possible in this case.

348 The cost for inspection  $C_{ndt}$  decreases when the flaw size increases, as the scan time is  
349 reduced. The optimum configuration can be found at a flaw size of 16.3mm. There, the  
350 active constraint switches from buckling to maximum strain and the objective function  
351  $DOC$  is 14% lower than the one of the baseline. Any further increase of the flaw size is  
352 disadvantageous, as the impact of the manufacturing cost due to additional material (to  
353 resist material failure) is too high.

354 *Quality optimization of the intermediate panel ( $p = \text{€}1500/\text{kg}$ )*

355 Second, an intermediate panel design with  $\text{€}1500/\text{kg}$  has been investigated. Similar to  
356 the preceding example, the cost of this panel was recalculated adding the cost for  
357 in-production and in-service inspection with a standard flaw size of 6mm. Then the  
358 panel has been optimized for a series of flaw sizes, see Table 3.

359 As seen before, the objective function is the highest for a very small flaw size of 2mm  
360 due to the high NDT cost. As the panel thicknesses are constraint by the active buckling  
361 condition, no weight or cost saving is possible for this laminate quality.

362 As long as buckling governs the design, an increased flaw size mainly results in lower  
363 NDT while the weight and the manufacturing cost remain the same. At a flaw size of  
364 12.4mm, buckling and maximum strain are active, and the  $DOC$  achieves its minimum  
365 at 96%. Any increase of flaw size results in increased weight and manufacturing cost,  
366 thus forcing up the objective function. The stringer cross-sections are very thick at flaw  
367 sizes of 14mm and 20mm due to the reduced strength. As the cross-sections are

368 extraordinarily thickened, more scanning is necessary in order to guarantee a probability  
369 of detection of 95%. The result is an increase of NDT cost, despite the existence of a  
370 lower laminate quality.

371 *Quality optimization of the low-weight panel ( $p = \infty/kg$ )*

372 Third, a weight optimized panel has been exposed to the inclusion of NDT cost. In  
373 Table 4, these results are shown. As the manufacturing and non-destructive testing costs  
374 are a very small part of this objective function, the *DOC* mainly depends on the weight.  
375 As anticipated, the optimum laminate quality is found at very small flaw sizes, and both  
376 structural constraints are active.

377 *Variation of the POD*

378 Non-destructive testing theoretically never reaches a probability of detection of 100%. In  
379 practice, an artificial limit is therefore set to this value, representing a measure of  
380 trustworthiness for the testing method. The effect of the *POD* limit on the results is  
381 now investigated.

382 The results shown in Table 5 apply for the intermediate panel with a weight penalty of  
383  $p = \infty/kg$ . As expected, the quality of laminate is not influenced by the *POD*, and  
384 the optimal design solution is found independently. On the other hand, an increase in  
385 NDT cost and thus an increase in the objective function can be seen for higher  
386 probabilities. This is the cost one has to account for when a higher NDT reliability is  
387 desired.

## 388 5 Conclusion

389 A framework for the cost/weight optimization of composite structures under  
390 consideration of a variable laminate quality has been proposed. A generic skin/stringer  
391 element has been adopted as a case study; the main focus has been brought to a  
392 parameter study in which the allowed flaw size was varied.

393 According to the definition of direct operating cost, an objective function has been  
394 selected that included manufacturing cost, in-production and in-service inspection and a  
395 weight penalty. Starting from a standard flaw size, the effects of the laminate quality on  
396 the objective function have been investigated. The optimal flaw size depends on the  
397 structure, the material data, the load case and the weight penalty; hence, it has been  
398 shown that cost savings are possible by revising the laminate quality already in the  
399 design phase. Nevertheless, the conclusions drawn here suggesting that the flaw size  
400 does not have to be 6 mm should be viewed as specific to the assumptions and analysis  
401 made and they may not be valid when, for example, fatigue is taken into account.  
402 Larger flaw sizes may shorten the fatigue life. Further work is needed in this area before  
403 the conclusions can be generalized.

404 This optimization framework may be used in applications outside the aerospace  
405 industry; as an example, one could consider its implementation for the production of  
406 rotor blades for windmills.

## 407 **6 Future Work**

408 The proposed optimization framework represents a first approach to include quality  
409 management aspects into the design process. More work, however, has to be done in  
410 order to improve the NDT cost and the NDT strength reduction model. First, the  
411 difference between in-production and in-service testing has to be more elaborate by  
412 applying different scanning techniques and overhead adjustments. Second, the strength  
413 reduction should be applied as a function of the stacking sequence, the material  
414 properties and the manufacturing technique. Third, it has to be investigated whether a  
415 stiffness reduction due to porosity should be included in the structural model. Fourth,  
416 the inspection interval should be adapted to the stress level and the structural function  
417 of each concerning member. And finally, a probabilistic damage model should be  
418 included to capture the failure and repair of a structural member. This could include a  
419 more detailed ultrasonic analysis, which in turn causes a cost increase.

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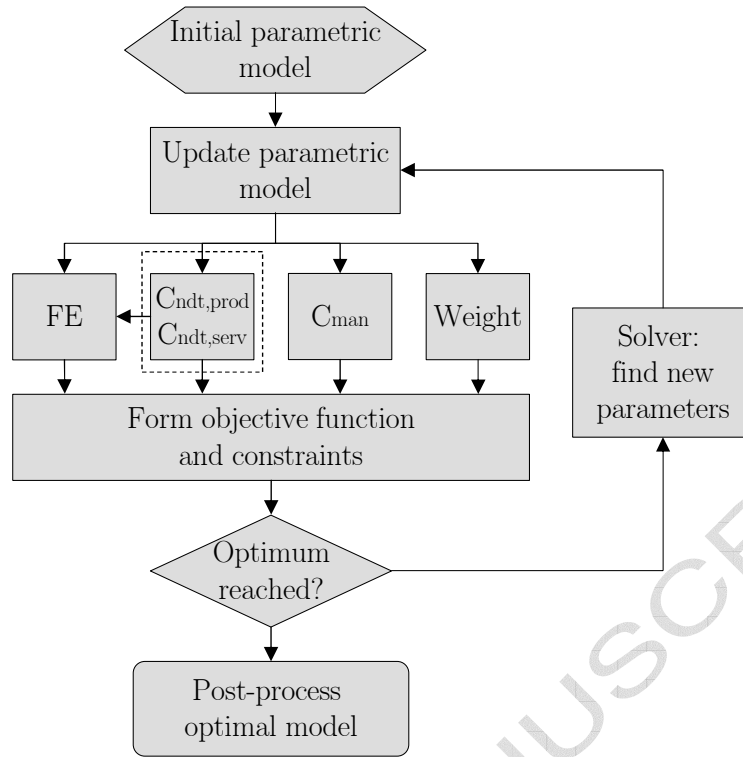


Fig. 1. The optimization loop; the module within the dashed line is subject to further explanation below.

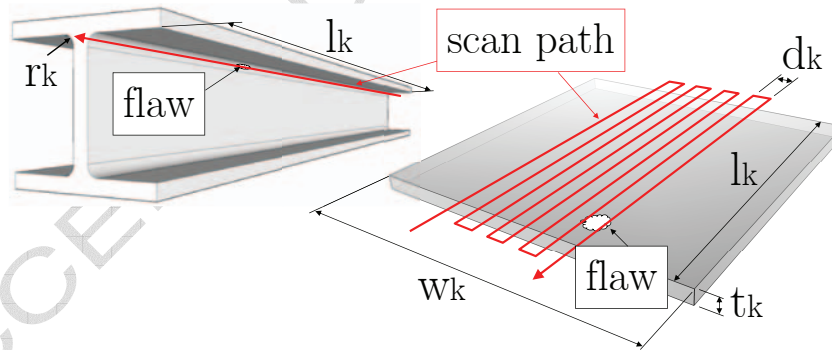


Fig. 2. Ultrasonic C-scan of radii and flat plates

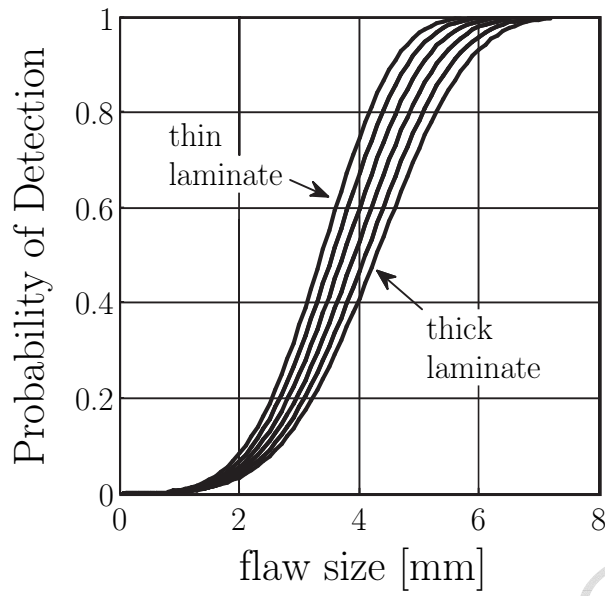


Fig. 3. Probability of Detection vs. maximum flaw size and laminate thickness

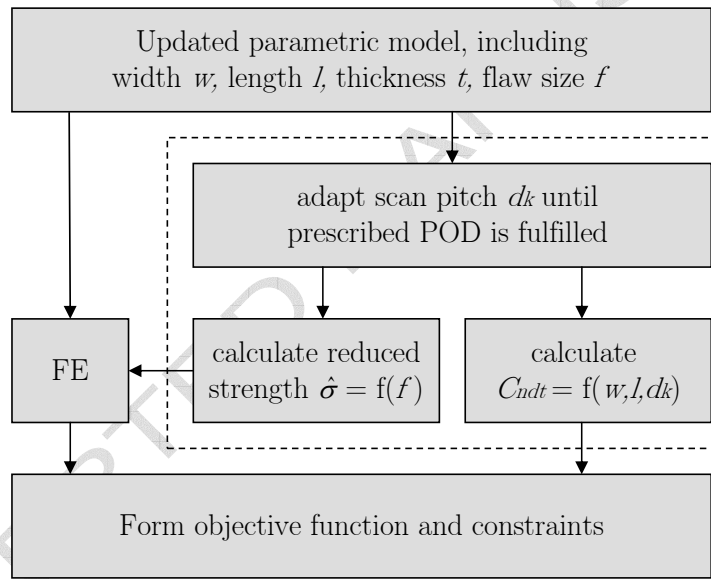


Fig. 4. Flow chart of the strength reduction and cost calculation mechanism for non-destructive testing of one single feature

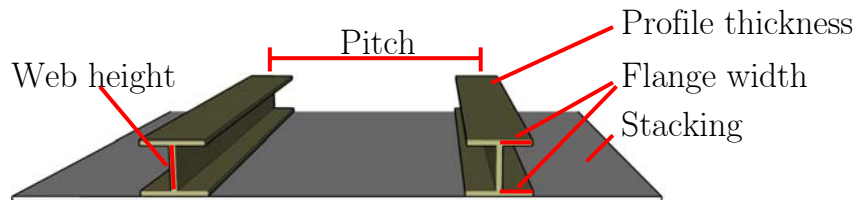


Fig. 5. Generic skin/stringer element



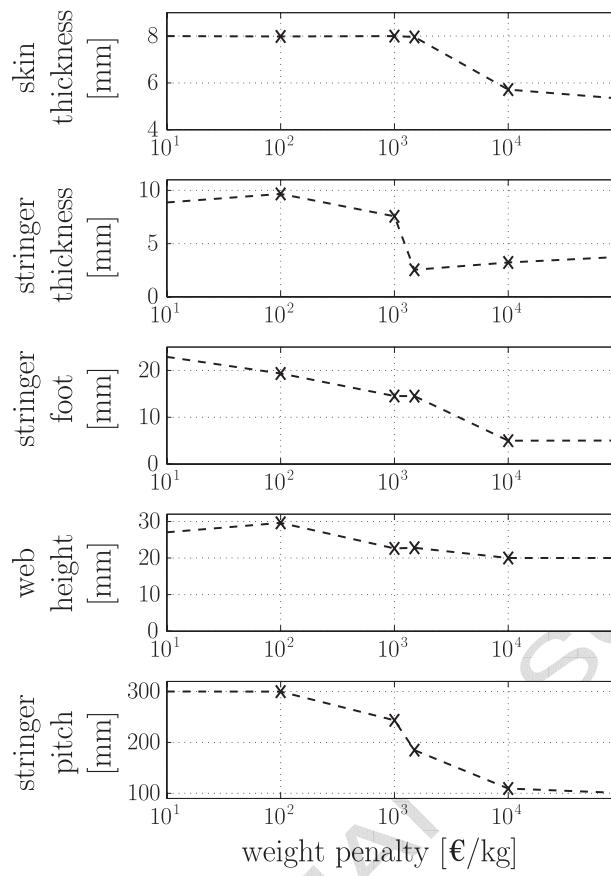


Fig. 6. Results from the preparatory parameter study

configuration	low-cost	intermediate	low-weight
$p$ [in €/kg]	0	1500	$\infty$
skin thickness [mm]	8.00	7.96	5.31
stringer thickness[mm]	8.88	2.53	3.77
stringer foot* [mm]	24.86	14.50	5.00
web height* [mm]	20.96	22.80	20.00
stringer pitch*[mm]	300.00	184.91	100.13

Table 1

Starting points for the investigation of different laminate qualities

flaw size	2mm	6mm	10mm	14mm	16.3mm	20mm
$DOC$	1.46	1.00	0.91	0.87	0.86	1.00
weight	1.00	1.00	1.00	1.00	1.00	1.14
$C_{ndt}$	2.74	1.00	0.66	0.51	0.46	0.46
$C_{man}$	1.00	1.00	1.00	1.00	1.00	1.19
buckling	1.00	1.00	1.00	1.00	1.00	0.92
MSTRN	0.58	0.58	0.67	0.81	0.92	1.00

Table 2

Quality optimization of the low-cost panel ( $p = \text{€}0/\text{kg}$ )

flaw size	2mm	6mm	10mm	12.4mm	14mm	20mm
$DOC$	1.16	1.00	0.97	0.96	1.00	1.37
weight	1.00	1.00	1.00	1.00	1.05	1.46
$C_{ndt}$	2.38	1.00	0.72	0.63	0.65	0.68
$C_{man}$	1.00	1.00	1.00	1.00	1.05	1.46
buckling	1.00	1.00	1.00	1.00	0.95	0.50
MSTRN	0.78	0.77	0.90	1.00	1.00	1.00

Table 3  
Quality optimization of the intermediate panel ( $p = \text{€}1500/\text{kg}$ )

flaw size	2mm	6mm	10mm	14mm	20mm
$DOC$	0.99	1.00	1.13	1.36	1.93
weight	0.99	1.00	1.13	1.36	1.93
$C_{ndt}$	2.07	1.00	0.85	0.75	0.74
$C_{man}$	1.00	1.00	1.15	1.24	1.36
buckling	1.00	1.00	0.82	0.48	0.22
MSTRN	1.00	0.98	1.00	1.00	1.00

Table 4  
Quality optimization of the low-weight panel ( $p = \text{€}\infty/\text{kg}$ )

$POD$	80%	85%	90%	95%	97.5%	99%
$DOC$	0.97	0.98	0.99	1.00	1.01	1.03
weight	1.00	1.00	1.00	1.00	1.00	1.00
$C_{ndt}$	0.76	0.81	0.89	1.00	1.11	1.24
$C_{man}$	1.00	1.00	1.00	1.00	1.00	1.00
buckling	1.00	1.00	1.00	1.00	1.00	1.00
MSTRN	0.78	0.78	0.78	0.78	0.78	0.78

Table 5  
Optimization with variable  $POD$  for the intermediate panel ( $p = \text{€}1500/\text{kg}$ )