Cost/Weight Optimization of Aircraft Structures

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Outline

- Motivation
- Aim of this work
- Multiobjective Optimization
- Paper A-C
- Future Work
Fuel Price

Data provided by Nordea Bank AB
Need for Weight Savings

- Fuel consumption of an A330
- 0.035 l/seat/km
- Average gross weight 200 tonnes
- 25 years, 300 days, 2·6000 km each day
- 100 million km
- 250 seats

- 1 billion liters of jet fuel
- 5000 liters per kg gross weight
- 1500-2000 € per kg gross weight at €0.4/l
Composites vs. Metals

Specific strength $\sigma/\rho$

Specific stiffness $E/\rho$

- Carbon/QI
- Titanium
- Glass/QI
- Magnesium
- Aluminum
- Steel

Switch to Composites

Composite Structural Weight [%]

- A300
- A310-200
- A320
- A340-300
- A340-600
- A350
- A380
- A400M
- A350

By courtesy of H. Assler, Airbus Deutschland GmbH
Composites vs. Metals

Main advantages
- Specific strength and stiffness
- Less corrosion
- Less fatigue problems, saving maintenance
- Composite can reduce the number of parts and fasteners

But
- Composite structures are more expensive to design and to manufacture
- Problems with the manufacturing of thick structures
- Rigorous non-destructive necessary
- Barely visible impact damage (BVID)
- Complex damage tolerance mananagement
Life-Cycle Cost

Aim of this work

Development of a cost/weight optimisation framework for aircraft structures

a) applicable for a variety of structures and manufacturing processes

b) arbitrarily expandable
   (e.g. for the introduction of a novel NDT cost module, or the sub-optimisation of manufacturing parameters)
Multiobjective Design Optimization

- Goal programming
  
  \[(\text{min } C_{\text{man}}) \text{ or } (\text{min } \text{Weight})\]

- Pareto Optimality

- Minimizing weighted sums
  \[F(x) = \sum_{i=1}^{n} \alpha_i f_i(x), \quad \alpha_i > 0, \quad i = 1, 2, \ldots, n\]
Direct Operating Cost (DOC)

\[
\text{DOC} = C_{\text{flight}} + C_{\text{maintenance}} + C_{\text{depreciation}} + C_{\lnr} + C_{\text{finance}}
\]

with

\[
C_{\text{flight}} = f(\text{crew, fuel, insurance})
\]
\[
C_{\text{maint}} = f(\text{maintenance, repair, overhaul})
\]
\[
C_{\text{depr}} = f(\text{price, flight hours})
\]
\[
C_{\lnr} = f(\text{landing and navigation fees, registry taxes})
\]
\[
C_{\text{fin}} = f(\text{financing strategy})
\]

Paper A

• Cost/Weight Optimization for different weight penalties

• The skin/stringer element

• Objective function

\[ \text{DOC} = \text{Cman} + p \times W \]
with \( p = \frac{\text{lifetime fuel burn cost}}{\text{component weight}} \)
Paper A

- design
- weight
- DOC
- solver
- objective function
- constraints
- FE
- ABAQUS
- Cman
- SEER-DFM
- DOC
- weight
- design
- constraints
- objective function
- solver
- Cman
- SEER-DFM
- FE
- ABAQUS
Paper A

composite skin
composite stiffeners

Low-cost design

Low-weight design

variables [mm]

weight penalty [€/kg]

- skin thickness
- foot width
- stringer thickness
- pitch
- web height
Paper A

![Graph showing DOC per unit width vs weight penalty for different configurations: all-metal, composite/metal, all-composite. The graph indicates that the all-metal configuration has the lowest DOC per unit width for a given weight penalty, followed by the composite/metal configuration, and then the all-composite configuration.](image-url)
The first conclusions

- more costs that describe the aircraft’s life-cycle should be included
- non-destructive testing
- maintenance and overhaul
NDT module

Input:
- type and geometry of the feature
- quality level (flaw size)
- prescribed probability of detection (POD)
- nominal strength

Output:
- NDT cost
- adapted scan pitch $d_k$
- reduced strength
NDT module

• Flaw sizes of less than 6mm can be applied, giving
  » higher NDT cost
  » thinner structure due to higher strength
  » lower structural weight and manufacturing cost

• Flaw sizes of more than 6mm can be applied, giving
  » lower NDT cost
  » thicker structure due to lower strength
  » higher structural weight and manufacturing cost.
• The skin/stringer element

• Division into 17 NDT features (i.e. laminates, radii and bonds)
  - NDT cost
  - scan pitch
  - material strength

• Objective function
  - \( \text{DOC} = C_{\text{man}} + C_{\text{ndt,prod}} + 5 C_{\text{ndt,serv}} + \text{€}1500/\text{kg} \times W \)
Some more conclusions

- Optimization of Direct Operating Cost including NDT
- Embedding of quality management into the design phase
  - Fine/coarse NDT scanning where necessary
  - High/low security factors where necessary
- The next step towards the optimization of the total life-cycle
  - $C_{\text{man}}$, $C_{\text{depr}}$, $C_{\text{maint}}$
- But: Not the lowest manufacturing cost possible for each given geometry
Future Work I

structural design

Pollutant Emissions

DOC / LCC

objective function

constraints

solver

FE

KTH Royal Institute of Technology
Future Work II

- Structural design
- Cutting of prepregs, layup, draping, curing
- DOC
  - Objective function
- Solver
  - Constraints

[Diagram: Flowchart showing the process involving structural design, cutting, DOC, objective function, solver, and constraints.]
Thank you for your attention.
Appendix: NDT Module

Input:
- type and geometry of the feature
- quality level (flaw size)
- prescribed probability of detection (POD)
- nominal strength

Output:
- NDT cost
- adapted scan pitch $d_k$
- reduced strength
NDT module

flaw size 6mm
scan pitch 2mm
PODmin 95%
allowable 0.40% $\varepsilon_{\text{compr}}$
NDT module

Probability of Detection

Flaw size [mm] 5mm
Scan pitch 2mm
PODmin 75%
Allowable 0.38% εcompr
NDT module

- Flaw size: 5mm
- Scan pitch: 1mm
- PODmin: 95%
- Allowable: 0.38% $\varepsilon_{\text{compr}}$
**Appendix: NDT Module**

![Diagram of a panel with labeled features](image)

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Panel thickness (mm)</th>
<th>Web height (mm)</th>
<th>Flange width (mm)</th>
<th>Profile thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>5</td>
<td>300</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Table of Features**

<table>
<thead>
<tr>
<th>Feature</th>
<th>L</th>
<th>W</th>
<th>t</th>
<th>r</th>
<th>Technique</th>
<th>Operator</th>
<th>Path [m]</th>
<th>Time [min]</th>
<th>Cost [€]</th>
</tr>
</thead>
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<td>['F1'] = 'Skin Laminate'</td>
<td>400</td>
<td>600</td>
<td>5</td>
<td>-</td>
<td>Squirter</td>
<td>Level 2</td>
<td>120</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>['F2'] = 'Str1 Horizontal Flange'</td>
<td>400</td>
<td>40</td>
<td>5</td>
<td>-</td>
<td>TT autom</td>
<td>Level 1</td>
<td>8</td>
<td>XX</td>
<td>XX</td>
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<tr>
<td>['F3'] = 'Str1 Horizontal Foot'</td>
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<td>40</td>
<td>5</td>
<td>-</td>
<td>TT autom</td>
<td>Level 1</td>
<td>8</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>['F4'] = 'Str1 Vertical Web'</td>
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<td>50</td>
<td>5</td>
<td>-</td>
<td>TT autom</td>
<td>Level 1</td>
<td>8</td>
<td>XX</td>
<td>XX</td>
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<tr>
<td>['F5'] = 'Str1 Radius 1'</td>
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<td>-</td>
<td>-</td>
<td>8</td>
<td>PE manual</td>
<td>Level 2</td>
<td>0.4</td>
<td>XX</td>
<td>XX</td>
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<tr>
<td>['F6'] = 'Str1 Radius 2'</td>
<td>400</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>PE manual</td>
<td>Level 2</td>
<td>0.4</td>
<td>XX</td>
<td>XX</td>
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<tr>
<td>['F7'] = 'Str1 Radius 3'</td>
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<td>-</td>
<td>-</td>
<td>8</td>
<td>PE manual</td>
<td>Level 2</td>
<td>0.4</td>
<td>XX</td>
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<tr>
<td>['F8'] = 'Str1 Radius 4'</td>
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<td>-</td>
<td>-</td>
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<td>XX</td>
<td>XX</td>
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<td>['F9'] = 'Str2 Horizontal Flange'</td>
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<td>40</td>
<td>5</td>
<td>-</td>
<td>TT autom</td>
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<td>['F10'] = 'Str2 Horizontal Foot'</td>
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<td>XX</td>
<td>XX</td>
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<td>0.4</td>
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<td>0</td>
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<td>8</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
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<td>40</td>
<td>0</td>
<td>-</td>
<td>PE autom</td>
<td>Level 1</td>
<td>8</td>
<td>XX</td>
<td>XX</td>
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</tbody>
</table>

**Total** | xx | xx