LIFE CYCLE ASSESSMENT OF ECOLOGICAL IMPROVED COMPOSITES FOR AVIATION – A REVIEW

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Content

‣ Background
‣ LCA methodology
‣ Selected results of literature survey
‣ Conclusions & Outlook
Background

Growing market for aviation [1]:
- Air traffic more than doubles in the next 20 years
- 4.5% growth of passenger traffic p.a. until 2035
- 32,425 passenger aircraft required over the next 20 years

Environmental challenges [2]:
- Climate change
- Loss of biosphere integrity (biodiversity loss and extinctions)
- Nitrogen and phosphorus flows to the biosphere and oceans
- Landsystem change
- …

Measures with potential to reduce aviation's environmental impact

- Aircraft configuration
- Propulsion / alternative fuels
- Aerodynamics
- Trajectory / flight path
- Energy management
- ... 
- Lightweight design
  - Fibre Reinforced Composites
    - CFRP, GFRP, GLARE, ...
  → All synthetic / man-made materials

→ Bio-fibres?
→ Bio resins?
→ Recycled fibres?
Fibre modification

Non-woven

Flame retardant

Hybrid Reinforcement

Bio-based resin

Bio-Fibres

Recycled carbon fibres

Electrical Conductive Toughener
How to assess potential environmental impacts?

- Life Cycle Assessment (LCA)
  - A method of analysing and quantifying the potential environmental impact of a product, process or activity.
- ISO 14040 & 14044
- Cradle-to-grave approach:
  - Extraction of raw materials → pre-treatment → production of a good → distribution → use-phase → waste management
- (Cradle-to-gate, gate-to-gate)

- LCA supports
  - Product development and improvement
  - Strategic planning / decision making
  - Public policy making
  - Marketing ("Greening" vs. Facts)
LCA framework: Four Phases

1. Goal & Scope
   Definition of the product system in terms of the system boundaries and a functional unit (reference unit)

2. Inventory Analysis (LCI)
   Data collection and calculation procedures to quantify the relevant inputs and outputs of the product system

3. Impact Assessment (LCIA)
   Connecting inventory data with specific environmental impact categories and the respective category indicators

4. Interpretation
   Compilation of findings from both LCI and LCIA to provide conclusions and recommendations

[EN ISO 14040]
LCA Phases: Goal & Scope

- Goal and Scope definition
  - Reasons for LCA?
  - Target audience?
  - System description and assumptions

- Functional Unit (FU)
  - Reference to relate inputs and outputs
    - Poor example: Compare on volume/mass basis
    - Better example: Functional equivalence!

- System boundaries
  - Technical system and nature
  - Geographical area (energy mix)
  - Exclusions / Cut-off threshold
LCA Phases: Inventory Analysis (LCI)

Raw-materials  Operating Materials  Energy  Other inputs

Pre-product  Process  Assembly  Use-phase  EOL

Emissions (air, soil, water)  Waste  Other outputs  Energy?  Recycled Material?
LCA Phases: Impact Assessment (LCIA)

Classification

- e.g. CO₂, N₂O, CH₄ → GHG

Characterisation

- e.g. GWP100
  - CO₂ = 1, CH₄ = 23 kg CO₂eq, 1 kg of N₂O = 298 kg of CO₂eq

Normalization

- e.g. greenhouse gas emissions EU-28 in 2015:
  - 4.419 Mt CO₂eq

Weighting

- e.g. aggregation of several normalized environmental impacts

Midpoint

- Fossil depletion, metal depletion, water depletion, natural land transformation, urban land occupation, agricultural land occupation, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, marine eutrophication, freshwater eutrophication, terrestrial acidification, ionising radiation, particulate matter formation, photochemical oxidants, human toxicity, ozone depletion, climate change.

Endpoint

- e.g. human health, ecosystem quality and resource depletion

Various LCIA-methodologies covering all environmental impacts:
- e.g. ReCiPe, CML2001, EDIP, EI99, ILCD, TRACI...
SoA materials for composites in aviation (LCA data)

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy (MJ/kg)</th>
<th>GHG (kg CO$_{2eq}$/kg)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>76-80</td>
<td>137</td>
<td>Michaud 2016</td>
</tr>
<tr>
<td></td>
<td>137</td>
<td>8.1</td>
<td>Plastics Europe</td>
</tr>
<tr>
<td></td>
<td>76-137</td>
<td>4.7-8.1</td>
<td>Deng 2014</td>
</tr>
<tr>
<td>Phenolic resin</td>
<td>-</td>
<td>7.0 (foam)</td>
<td>Densley 2014</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td></td>
<td>Suzuki 2005</td>
</tr>
<tr>
<td></td>
<td>102 (incl. FRP manuf.)</td>
<td>5.8</td>
<td>Moliner 2013</td>
</tr>
<tr>
<td>Carbon fibres</td>
<td>286 (186-360)</td>
<td>22.4</td>
<td>Michaud 2016</td>
</tr>
<tr>
<td></td>
<td>1 122</td>
<td>53 (std)</td>
<td>Verpoest 2014</td>
</tr>
<tr>
<td></td>
<td>286-704</td>
<td>24.4-31</td>
<td>Deng 2014</td>
</tr>
<tr>
<td></td>
<td>286 (JMCA 2004)</td>
<td>-</td>
<td>Suzuki 2005</td>
</tr>
<tr>
<td></td>
<td>286 (JMCA 2009)</td>
<td>-</td>
<td>Zhang 2009</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>45.6</td>
<td>2.5</td>
<td>Michaud 2016</td>
</tr>
<tr>
<td></td>
<td>21.1</td>
<td></td>
<td>Dai 2015</td>
</tr>
<tr>
<td></td>
<td>13-32</td>
<td></td>
<td>Song 2009</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>2.6</td>
<td>Deng 2014</td>
</tr>
<tr>
<td></td>
<td>10.3 glass 30 (incl. comp manuf.)</td>
<td>1.6</td>
<td>Moliner 2013</td>
</tr>
<tr>
<td>Aramid paper</td>
<td>-</td>
<td>-</td>
<td>none</td>
</tr>
</tbody>
</table>
Composites in Aviation (LCA)

- Composites for structural applications are commonly more energy intensive during production phase.
- The use-phase is very important for transportation, especially for emissions from energy consumption.
- Composites, if designed optimal, can surpass classic metals during the use-phase because of lighter weight and less fuel consumption.
- Therefore it is of highest importance to assess the complete life-cycle of an airplane and not only a cradle-to-gate approach.
Natural Fibres

Flax (Linum usitatissimum)

Ramie (Boehmeria nivea)

[Wang et al 2015]
Natural Fibres
LCA example: NFRP vs. GFRP

Bio-resins
Bio-resins (LCA example)

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Units</th>
<th>Petroleum based epoxy</th>
<th>Bio-based epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADP</td>
<td>kg Sb eq.</td>
<td>59.4</td>
<td>0.01</td>
</tr>
<tr>
<td>AP</td>
<td>kg SO2 eq</td>
<td>40.3</td>
<td>25.44</td>
</tr>
<tr>
<td>EP</td>
<td>kg PO4 eq</td>
<td>6.6</td>
<td>6.9</td>
</tr>
<tr>
<td>GWP</td>
<td>kg CO2 eq</td>
<td>6663</td>
<td>4079</td>
</tr>
<tr>
<td>ODP</td>
<td>kg CFC11 eq</td>
<td>1.26E-06</td>
<td>0.0</td>
</tr>
<tr>
<td>HTP</td>
<td>kg 1.4 DB eq</td>
<td>490.44</td>
<td>545.17</td>
</tr>
<tr>
<td>FAETP</td>
<td>kg 1.4 DB eq</td>
<td>246.5</td>
<td>66.39</td>
</tr>
<tr>
<td>TETP</td>
<td>kg 1.4 DB eq</td>
<td>29.1</td>
<td>228.63</td>
</tr>
<tr>
<td>CED</td>
<td>MJ eq</td>
<td>2.16</td>
<td>1.9</td>
</tr>
</tbody>
</table>

a Environmental impact results obtained using data from Ecoinvent v.2 database.
b Environmental impact results purchased by Entropy resin.
*) 48 % bio-content [Entropy Resins Inc. - Technical Data Sheet – Super Sap™ 100 Epoxy Resin/Super Sap™ 1000 Hardener]

Waste hierarchy

Product

PREVENTION

Waste

RE-USE

RECYCLING

RECOVERY

DISPOSAL
Recycling (Thermoset Composites)

Mechanical Recycling
- Fibrous and ground shares
  - Reinforcement or filler for composite production

Thermal Recycling
- Pyrolysis
  - Organic substances, gases and fibres with energy recovery
- Fluidized Bed
  - Gases and fibres with energy recovery

Chemical Recycling
- Solvolysis at low temperature
- Solvolysis in near- or super-critical liquids
  - Organic substances, anorganic compounds and fibres with energy recovery

Recycled fibres can be reused as reinforcement for composite production
rCF (LCA example)

Breakeven for material reuse in an automotive application

$(CO_2)_{eq}$ emissions

<table>
<thead>
<tr>
<th>kg CO$_2$ eq</th>
<th>Use Distance (km x $10^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>140</td>
<td>175</td>
</tr>
<tr>
<td>160</td>
<td>200</td>
</tr>
</tbody>
</table>

- VCF (1.51 kg)
- RCF (1.52 kg)
- VGF (2.54 kg)

Summary & Outlook

- LCA is an important tool to support the decision making

- Available results show advantages for bio-based composite materials and recycled carbon fibres, but:
  - Data quality is not always clear and assumptions lead to uncertainties

- Assessment of the complete life cycle, including use-phase
- Consider functional equivalence and material degradation
- Data quality of high importance for correct results

- In the ECO-COMPASS project, several case-studies on use-cases in Interior and Secondary Structures to compare „eco-materials“ with SoA will be assessed by LCA.
- Technologies for improvement of composite properties, e.g. nano particles/cellulose, plasma need to be included.
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谢谢大家的关注。

THANK YOU FOR YOUR ATTENTION.

WWW.ECO-COMPASS.EU