Reference Flows for Lightweight Materials in Transportation Systems

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Functional Units & Reference Flows

- The **functional unit**:
  - Is a measure of the performance of the functional outputs of a product system.
  - Is intended to provide a reference to which the inventory data are related to ensure alternatives are compared on a common basis.
- The **reference flow:**
  - Is amount of product necessary per functional unit, for each product system or alternative being assessed.
  - Dictate up and downstream process alternatives.

Functional Units & Reference Flows

- **Specification of the functional unit consists of:**
  - The magnitude of service
  - The duration of service, including the product's life span.
- **Definition of the functional unit and reference flows can be difficult due to issues related to:**
  - **lifetime** (subject to customer habits and non-systematic variations)
  - **performance** (subject to customer habits, the introduction of alternatives, and multi-functionality)
  - **system dependencies** (changes in the system design that result from changes in component design)

Specifying the Functional Unit & Reference Flows

- **Differentiation between the system and sub-system functions and solutions**
  - If the subject of the LCA is part of a larger system, the differentiation between the system and sub-system functions is needed to specify the functional unit and reference flows at both levels.
  - As an example,
    - The sub-system function for the cockpit of an automobile might be ‘house occupants and controls’
    - The system function for an automobile might be ‘transporting occupants and goods’
      - Any change in the amount of power needed to move the vehicle that is dependent on the mass and aerodynamics of the cockpit should be included in the functional units and reference flows.

Specifying the Functional Unit & Reference Flows

- **Specification of the functional unit**
  - For the system and the sub-system of interest, the functional unit needs 3 parts:
    - (1) the magnitude of service,
    - (2) the duration of service including the product's life span, and
    - (3) the expected level of quality.
  - As an example,
    - The magnitude and duration of service for the **fuel tank** might be 'MJ stored over 12 years' the expected level of quality might include 'without leaking.'
    - The magnitude and duration of service for the **automobile** might be 'transport of a 136 kg payload 233,000 km over 12 years,' the expected level of quality might be 'while maintaining range, acceleration, and hill climbing capacity.'

Specifying the Functional Unit & Reference Flows

- **Definition of the reference flows**
  - For the system and the sub-system of interest, the reference flows include the type and quantity of materials and energy necessary per functional unit including:
    - At the system level, **material and energy flows that change for sub-system alternatives**
    - At the sub-system level, any **solution-specific interface materials** (materials used as finishes or in joining, securing, shielding, piping, conditioning equipment, etc.)

Specifying the Functional Unit & Reference Flows

- **Definition of the reference flows**
  - For example,
    - At the sub-system level, the reference flows for a comparison of a **steel and a HDPE gasoline fuel tank** might include the tank, paint, straps, a shield, and related fasteners that change dependent upon the sub-system design
    - At the system level, because the steel tank and the solution-specific interface materials weigh more than that of the HDPE tank, **enhancements to the power train and the rest of the vehicle** made from steel, iron, and aluminum, etc. and the fuel increment over the product life would be included for the steel tank

Specifying the Functional Unit & Reference Flows

- **Interpretation of the functional unit and reference flows.**
  - Data Quality Information
    - Time coverage, geographic coverage, technology coverage, precision and completeness and representativeness of the data, sources of data and their representativeness, consistency and reproducibility of the methods used
  - Uncertainty Information
    - Assumptions
    - Limitations

Case Study: comparison of lightweight materials

- **System**: an aircraft
- **Sub-system**: plates made from four materials:
  - a wrought aluminum alloy
  - a cast aluminum alloy
  - an epoxy laminate- carbon prepreg composite
  - a titanium/silicon carbide composite

Comparison of Lightweight Aircraft Materials

- **Differentiation between the system and sub-system functions and solutions**
  - **Aircraft function:** "to facilitate transport of a certain payload."
  - **Plate function:** "to provide only allowable deflection for a certain load within a certain design footprint."

Comparison of Lightweight Aircraft Materials

- **<u>Specification of the functional unit</u>**
  - The functional unit for the aircraft is "20,455 kg payload moved over 30 years while maintaining range, radius, time on station, and speed."

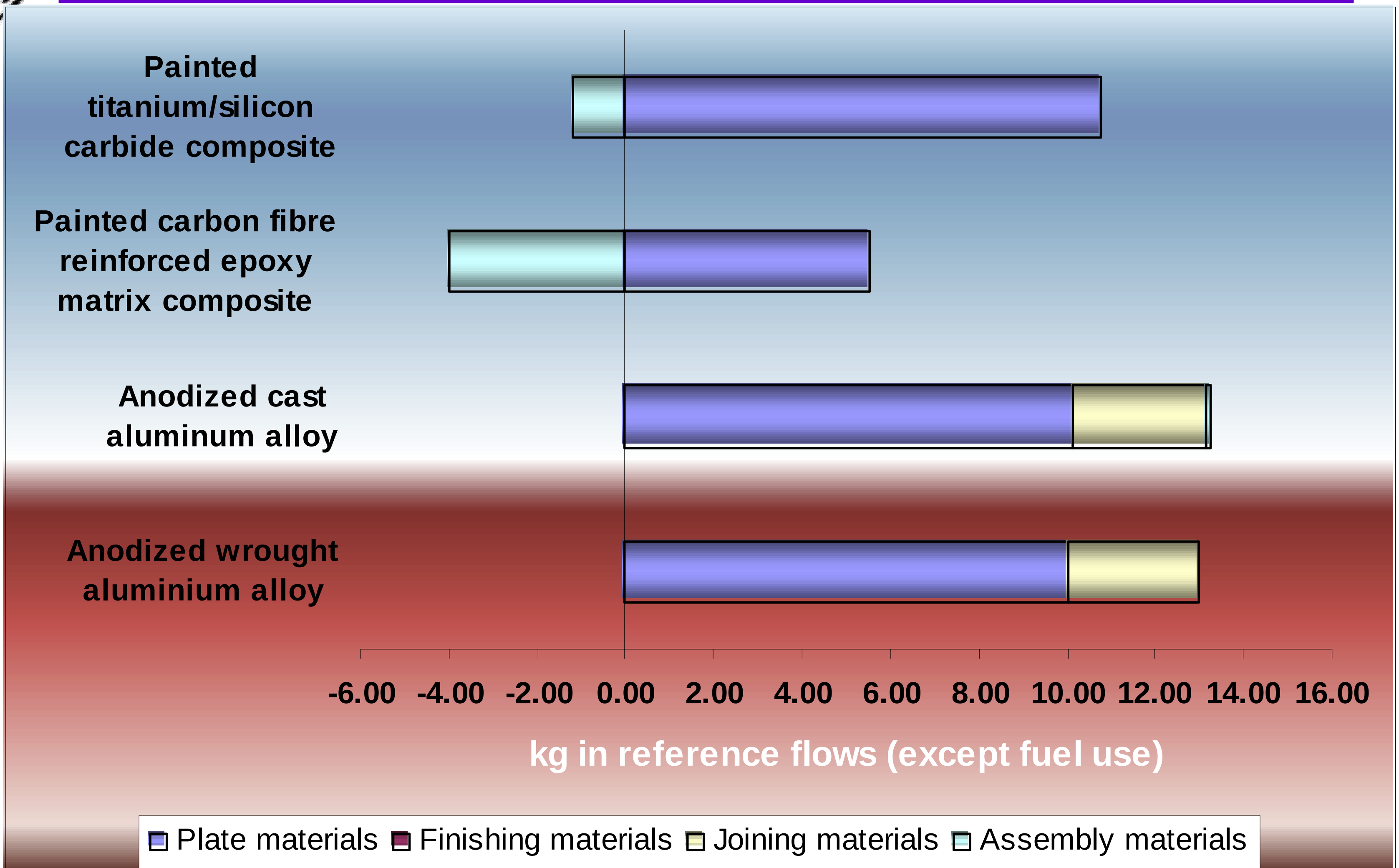
magnitude

duration

expected level of quality

  - The functional unit for the aluminum and composite plates is "equivalent stiffness to aluminum within an area of 0.3 m^2 (with length of 0.5 m and width of 0.6 m)."

Comparison of Lightweight Aircraft Materials



Comparison of Lightweight Aircraft Materials

Plate Materials	**Anodized wrought aluminium alloy (kg)**	**Anodized cast aluminum alloy (kg)**	**Painted carbon fibre reinforced epoxy matrix composite (kg)**	**Painted titanium/silicon carbide composite (kg)**
Wrought aluminium alloy	10.00			
Cast aluminum alloy		10.15		
Epoxy Laminate (EP) - Carbon Prepreg			5.54	
Titanium/Silicon Carbide Composite				10.79
Finishing Materials				
Primer, sealer, topcoat	none on part	none on part	1.1E-03	1.1E-03
Joining Materials				
Steel bolts	3.00	3.00		
Adhesive			3.2E-06	3.2E-06
Total plate, finishing, and joining materials	**13.00**	**13.15**	**5.54**	**10.79**
Assembly Materials				
Aluminum		6.6E-02	-3.2E+00	-9.5E-01
Steel		8.3E-03	-4.0E-01	-1.2E-01
Titanium		4.1E-03	-2.0E-01	-5.9E-02
Other materials		4.1E-03	-2.0E-01	-5.9E-02
Lifetime fuel consumption (/ 30 years)		701	-33,961	-10,060

Comparison of Lightweight Aircraft Materials

- **Interpretation of the functional unit and reference flows**
  - **Data Quality Information**
    - Time and technology coverage (applies to current aircraft)
    - Geographic coverage (not considered)
    - Precision, completeness, representativeness of the data (the SAWE model used is assumed to apply to conceptual aircraft design)
    - Sources of data and their representativeness (although primary data from the Boeing Company were used in the related LCA, no primary data have been included here)
    - Consistency and reproducibility of the methods used (methods are based on sound engineering principles captured by the linear and parametric models used; because all models and data used are publicly available, the analysis is reproducible; the models have, however, not been validated for this application)

Comparison of Lightweight Aircraft Materials

- **Interpretation of the functional unit and reference flows**
  - Uncertainty Information: **Assumptions**
    - Sub-system
      - Mechanical properties dominate material selection.
      - Anodizing aluminum plates and painting composite plates is sufficient to ensure no mid-life replacement is necessary such that no system expansion or allocation of co-products is required for the inventory analysis.
    - System
      - The turbojet will carry a payload of 20,455 kg and the constant portion of the empty aircraft mass is 20,000 kg. The empty aircraft mass is based on a thrust-to-weight ratio of 0.28, a thrust-to-engine ratio of 5, a structural weight fraction of 0.425, the ratio of the mission fuel mass to the gross aircraft mass is 0.24, and the reserve fuel factor is 0.2.
      - The mass fraction for the variable portion of the empty aircraft mass is 0.25. It has also been assumed that the variable portion of the aircraft mass varies linearly with the gross mass and that any increase can be represented by an even distribution of 80% aluminum, 10% steel, 5% titanium, and 5% other materials.

Comparison of Lightweight Aircraft Materials

- **Interpretation of the functional unit and reference flows**
  - Uncertainty Information: **Limitations**
    - System
      - The categorization of systems into constant and variable mass portions is approximate as each of the variable mass does not vary linearly with the gross aircraft mass.
    - Sub-system
      - The function of a product is rarely one-dimensional, strict measurement of the function covers only a part (although the relevant one) of the comprehensive set of functions.

Comparison of Lightweight Aircraft Materials

- **Interpretation of the functional unit and reference flows**
  - Uncertainty Information: **Limitations**
    - Analysis of product features not included in the functional unit or the quantification of the reference unit as better, similar, or worse than the baseline

	Recycled fraction	Flammability	Protection from Fresh Water	Protection from Organic Solvents	Protection from Sea Water	Protection from Strong Acid	Protection from Strong Alkalis	Protection from UV	Protection from Wear	Protection from Weak Acids	Protection from Weak Alkalis
Wrought aluminum alloy	BASELINE										
Cast aluminum alloy	S	S	S	S	S	S	S	S	S	S	S
Epoxy laminate- carbon prepreg	-	-	S	-	S	-	+	-	S	S	S
Titanium/silicon carbide composite	-	+	S	S	+	-	+	S	+	S	+

Basis for the Suggested Requirements

- Differentiation between the system and sub-system functions and solutions.
- Specification of the functional unit to include the magnitude of service, the duration of service including the product's life span, and the expected level of quality.
- Specification of the reference flows to include system-level flows that change for sub-system alternatives and any solution-specific interface materials (materials used as finishes or in joining, securing, shielding, piping, conditioning equipment, etc.).
- Interpretation including information needed for the analysis of data quality and uncertainty and a discussion of assumptions and the limitations.

Suggested Requirements

- **Definition of the reference flows.**
  - Also, if the life of the sub-system is less than the duration specified in the functional unit, multiple sub-systems should be included in the reference flows without artificially partitioning components (i.e., reference flows should not include ½ of a car but might include ½ of a kg of aluminum).
  - Finally, if the life of sub-system exceeds the duration specified in the functional unit, the sub-system remaining at the end-of-life should be treated either as a co-product or waste of the system during inventory analysis.

Discussion

- Consideration of reference flows at the systems level and at interfaces **influenced** aircraft fuel use, the identity of up and downstream processes considered in the LCA, and related impacts.
- The **expected level of quality** was required to be constant at the system level. Variations at the sub-system level were assumed not to be severe enough to impact component life and were an important part of the interpretation of results.
- Additional information can be found in: Cooper, J.S. (2003) “Specifying Functional Units and Reference Flows for Comparable Alternatives,” accepted for publication in the *International Journal of Life Cycle Assessment*.

Discussion

- Opportunities for additional research include:
  - Provide methods to capture the influence of consumer habits and lifetime variations (Monte Carlo Analysis, failure analysis).
  - Illustrate how system performance impacts systems other than aircraft. For example:
    - Other transportation systems.
    - In a PC, as the processing speed increases, do the cooling and power supply system need to be augmented?
    - Is the nutritional value of food impacted by the use of pesticides?
    - Does the addition of insulation to a house allow smaller heating and air conditioning systems to be used?
  - Investigate further what materials must be included and what can be ignored.

Suggested Requirements for Specifying the Functional Unit and Reference Flows in Comparative LCAs

1. **Differentiation between the system and sub-system functions and solutions.** If the subject of the LCA is part of a larger system, a statement shall be provided differentiating between the system and sub-system functions. Each function should be presented as a task that is independent of any particular solution. At both the system and sub-system levels, a description of how solutions are consistent with the goal and scope of the study shall be included. Also, a description of the particular sub-system solutions to be assessed shall be included.

2. **Specification of the functional unit.** For the system and the sub-system of interest, a statement of the functional unit shall include 3 parts: (1) the magnitude of service, (2) the duration of service including the product's life span, and (3) the expected level of quality. Also, when comparing particular sub-system solutions, the functional unit should be the same at the systems level.

3. **Definition of the reference flows.** For the system and the sub-system of interest, definition of the reference flows shall include the type and quantity of materials and energy necessary per functional unit. At the system level, material and energy flows that change for sub-system alternatives should be included in the reference flows. At the sub-system level, any solution-specific interface materials (materials used as finishes or in joining, securing, shielding, piping, conditioning equipment, etc.) should be included in the reference flows.

   Also, if the life of the sub-system is less than the duration specified in the functional unit, multiple sub-systems should be included in the reference flows without artificially partitioning components (i.e., reference flows should not include ½ of a car but might include ½ of a kg of aluminum). Finally, if the life of sub-system exceeds the duration specified in the functional unit, the sub-system remaining at the end-of-life should be treated either as a co-product or waste of the system during inventory analysis.

4. **Interpretation of the functional unit and reference flows.** For the system and the sub-system of interest, interpretation of the functional unit and reference flows shall include information needed for the analysis of data quality and uncertainty. Also, a discussion of assumptions and the limitations of the methods used should include an analysis of product features not included in the functional unit or the quantification of reference flows.