APPENDIX - life cycle Formulas

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The following are calculations which aim to clearly, simply, and without any layers of abstractions explain the formulas used in the excel document. Latex has been used for its superior mathematical notation. Further, in excel a note should be made that SUMIFS, IFS, and VLOOKUPS were used to sort masses and materials automatically, as can be seen in the excel document.

Material Life Phase

To calculate the **Material Life Phase Energy**, which accounts for the energy required for material extraction, transport, and processing, we use the following formula:

$$E_{\text{material}} = \sum_{i=1}^{n} (H_{m,i} \times M_{m,i} \times Q_i)$$

Where:

- $H_{m,i}$ is the Embodied Energy density (in MJ/kg) of each material i.
- $M_{m,i}$ is the Mass (in kg) of each material i used in the product.
- Q_i is the Quantity of components for each material i (number of units).

Additionally, the **Material Life Phase Carbon Footprint** is calculated as:

$$\text{CO}_2\text{eq}_{\text{material}} = \sum_{i=1}^{n} (\text{CO}_2\text{eq}_i \times M_{m,i} \times Q_i)$$

Where:

- CO_2eq_i is the CO2 equivalent (in kg) for each kg of material i.

Manufacturing Life Phase

The **Manufacturing Life Phase Energy** considers both primary and secondary processes. The energy is calculated using:

$$E_{\text{manufacturing}} = \sum_{i=1}^{n} (P_{p,i} \times M_{m,i} \times Q_i) + \sum_{j=1}^{m} (\text{SpE}_j \times D_j \times Q_j)$$

Where:

- $P_{p,i}$ is the Primary Process Energy per unit mass for each material i (in MJ/kg).
- SpE_j is the Secondary Process Energy per unit dimension for each process j.
- D_j is the dimension (such as surface area, volume, length, etc.) for each process j. This is also scaled by the quantity Q_j.
- $M_{m,i}$ and Q_i are the Mass and Quantity for each material i as previously defined.

Similarly, the **Manufacturing Life Phase Carbon Footprint** can be calculated by:

$$\text{CO}_2\text{eq}_{\text{manufacturing}} = \sum_{i=1}^{n} (P_{p,i} \times M_{m,i} \times Q_i) + \sum_{j=1}^{m} (\text{SpC}_j \times D_j \times Q_j)$$

Where:

- SpC_j is the Secondary Process CO2 equivalent per unit dimension for each process j.

Transportation Life Phase

The **Transportation Life Phase Energy** is calculated as:

$$E_{\text{transportation}} = \sum_{k=1}^{p} (\text{TEF}_k \times P_m \times X_k)$$

Where:

- TEF_k is the Transport Energy demand per unit mass per km for each stage k (in MJ/metric ton.km).
- P_m is the Total Mass (in kg) of the product and its contents.
- X_k is the Distance (in km) for each transportation stage k from the point of production to the point of use.

Similarly, the **Transportation Life Phase Carbon Footprint** is given by:

$$\text{CO}_2\text{eq}_{\text{transportation}} = \sum_{k=1}^{p} (\text{TCF}_k \times P_m \times X_k)$$

Where:

- TCF_k is the Transport Carbon emissions per unit mass per km for each stage k (in kg/metric ton.km).

Use Phase

The **Use Phase Energy** is calculated as:

$$E_{\text{use}} = \sum_{i=1}^{n} \left(\frac{\text{PEU}_i \times D \times \text{CF}_i}{\text{CE}_i} \times \text{PRp}_i \times \text{DC}_i \times \text{PL}_i \right)$$

Where:

- PEU_i is the Source of Primary Energy for use i.
- D is the volume of the product $[\text{m}^3]$
- CF_i is the Conversion Factor for oil equivalent for each source i.

- CE_i is the Conversion Efficiency for each source i.
- PRp_i is the Power Rating of the product (e.g., kW/m^3 for refrigeration).
- DC_i is the Duty Cycle, considering product life, days per year, and hours per day.
- PL_i is the Product Life in years.

Similarly, the **Use Phase Carbon Footprint** is given by:

$$\mathrm{CO_2eq_{use}} = \sum_{i=1}^{n} \left(\frac{\mathrm{PCU}_i \times D \times \mathrm{PRp}_i \times \mathrm{DC}_i \times \mathrm{PL}_i}{\mathrm{CE}_i} \right)$$

Where:

- PCU_i is the Carbon Dioxide associated with the primary energy conversion for each source i.

Disposal (End of Life) Phase

For the disposal phase, energy and carbon footprints are calculated based on the method of disposal: recycling, landfill, or combustion. The formulas differ depending on whether the scenario results in a debit or a credit. Please refer to the variable meanings at the end of this section.

Recycling

Debit

- **Energy:**

$$E_{\text{recycle, debit}} = \sum_{i=1}^{n} \left(\tilde{H}_i + (1 - r_i) H_{d,i} \right) \times \mathrm{mass}_i \times Q_i$$

- **CO2:**

$$\mathrm{CO_2eq}_{\text{recycle, debit}} = \sum_{i=1}^{n} \left(\tilde{C}_i + (1 - r_i) C_{d,i} \right) \times \mathrm{mass}_i \times Q_i$$

Credit

- **Energy:**

$$E_{\text{recycle, credit}} = \sum_{i=1}^{n} r_i \left(\tilde{H}_i - H_{c,i} \right) \times \mathrm{mass}_i \times Q_i$$

- **CO2:**

$$\mathrm{CO_2eq}_{\text{recycle, credit}} = \sum_{i=1}^{n} r_i \left(\tilde{C}_i - C_{c,i} \right) \times \mathrm{mass}_i \times Q_i$$

Landfill

Debit

- **Energy:**

$$E_{\text{landfill}} = \sum_{i=1}^{n} H_{d,i} \times \mathrm{mass}_i \times Q_i$$

- **CO2:**

$$\mathrm{CO_2eq}_{\text{landfill}} = \sum_{i=1}^{n} C_{d,i} \times 0.01 \times \mathrm{mass}_i \times Q_i$$

Combustion

Debit

- **CO2:**

$$\mathrm{CO_2eq}_{\text{combust}} = \sum_{i=1}^{n} a_i \times H_{c,i} \times \mathrm{mass}_i \times Q_i$$

Credit

- **Energy:**

$$E_{\text{combust}} = \sum_{i=1}^{n} \eta_c \times H_{c,i} \times \mathrm{mass}_i \times Q_i$$

Note: For variable meanings, refer to the following:

- $H_{d,i}$ and $C_{d,i}$ are the energy and carbon debits for landfill per unit mass for material i.
- $H_{c,i}$ and $C_{c,i}$ are the energy and carbon values associated with combustion per unit mass for material i.
- $\tilde{H}_i$ and $\tilde{C}_i$ are the effective embodied energy and carbon footprint per unit mass for material i.
- r_i is the recycled content fraction for material i.
- η_c is the combustion efficiency, typically $\eta_c = 0.25$.
- a_i is the combustion carbon factor per unit mass for material i, typically $a_i = 0.07\,\mathrm{kg\ CO_2/MJ}$.

The effective embodied energy $\tilde{H}_i$ and carbon footprint $\tilde{C}_i$ are calculated as:

$$\tilde{H}_i = r_i H_{rc,i} + (1 - r_i) H_{m,i} \quad \mathrm{MJ/kg}$$

$$\tilde{C}_i = r_i C_{rc,i} + (1 - r_i) C_{m,i} \quad \mathrm{kg\ CO2/kg}$$