Realising the Transition towards the Circular Economy

Hybrid LCA

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Session Objectives

- ✓ To gain some technical insight into how to construct a Hybrid LCA model.

Types of LCA Methodologies

- Process/Traditional LCA
- Environmental Input-Output (EIO)
- Hybrid LCA (combines Process and EIO)

Main issues related to LCA Methodology

- The ACCURACY of the Data
- ROBUSTNESS of the Methodology
- The COMPLETENESS of the System Boundary

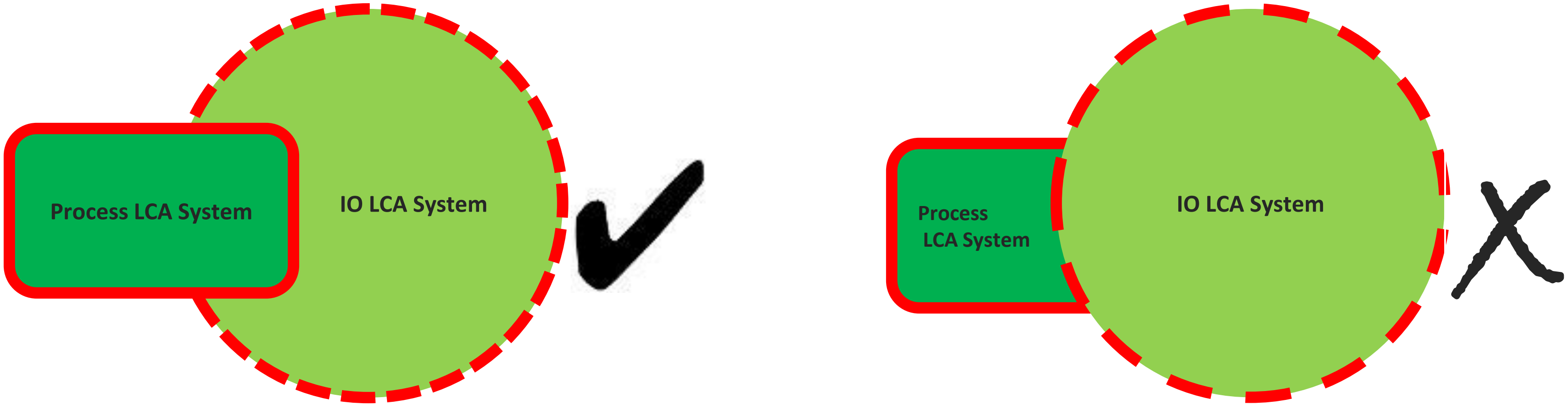
Differences in the Methodologies

Combine the Methods

Process/Traditional LCA	Environmental Input-Output
➢ Bottom-Up approach	➢ Top-Down approach
➢ Subjective System Boundary	➢ Extended System Boundary
➢ More accurate (specific)	➢ Less accurate (generic)
➢ Data and Time Intensive	➢ Less Data and Time Intensive
➢ Physical Perspective	➢ Economic perspective
➢ Data confidentiality	➢ Freely available data

Hybrid LCA System

Combine the Process LCA system and Environmental LCA system



Hybrid LCA system is more ROBUST because of the Specificity and Accuracy of Process LCA and the System Boundary Completeness of IO LCA

The Integrated Hybrid LCA System

- Generally Input-Output accounts are less reliable than process-specific data due to temporal differences between IO data and current process operation, aggregation, import assumptions.

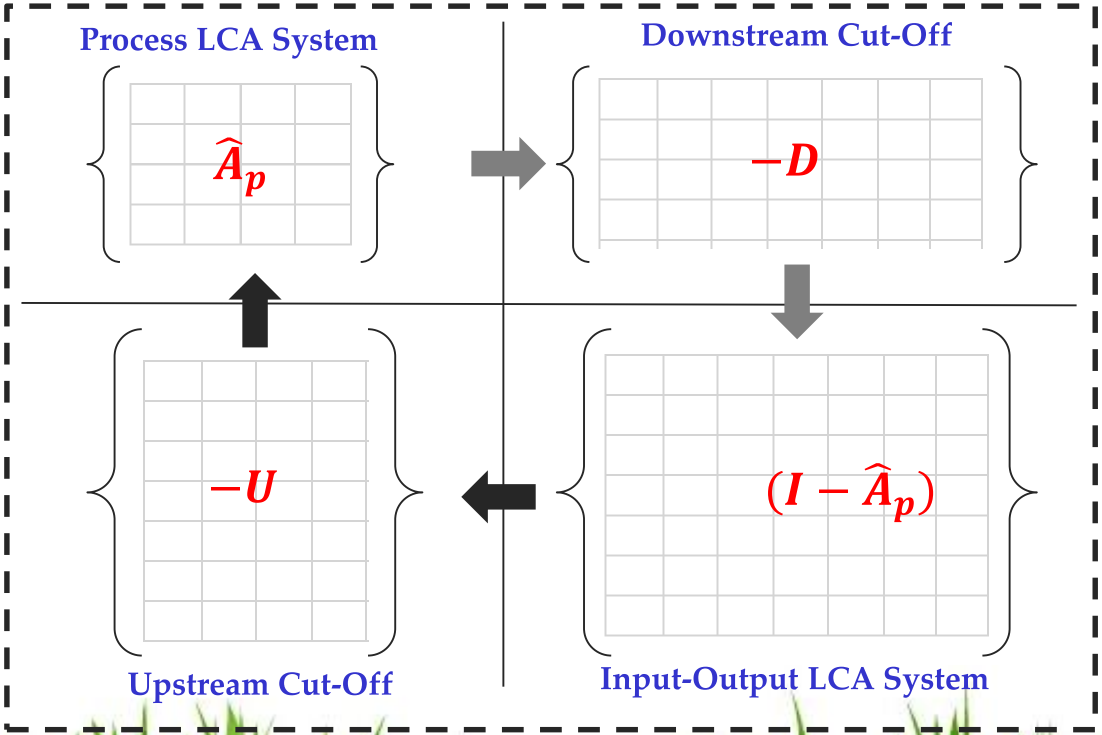
- The Input-Output table is therefore interconnected with the matrix representation of the physical product system (that is, the LCA Process system) only at upstream and downstream cut-offs where better process data are not available.

The Integrated Hybrid LCA System

$$Hybrid\ LCA_{integrated} = \begin{bmatrix} \hat{E}_p & 0 \\ 0 & \hat{E}_{p(m)i-o} \end{bmatrix} \cdot \begin{bmatrix} \hat{A}_p & -D \\ -U & \hat{A}_{i-o} \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix}$$

(Suh and Huppes, 2005)

The LCA System is inverted using Matrix Inversion.



Setting Up the Process LCA System

$$LCA\ Impacts_{(i)} = \sum_{m=1}^{n} Q_m \times\ e_{i(m)}$$

Using the simplest of LCA method called Process LCA, the LCA Impacts across indicator (i) (example: Global Warming Potential, impact on human health, etc) can be calculated as the product-sum of the Quantities of all Materials (m) and the Impact Intensities (e) of indicator (i) of Material (m).

❖ This can be represented in matrix form as:

$$LCA_p = \hat{E}_p . \hat{A}_p^{\ -1} . \hat{y}_p$$

Setting Up the Process LCA System

In matrix form, the Process LCA can be represented as:

$$LCA_p = \hat{E}_p . \hat{A}_p^{-1} . \hat{y}_p$$

$\hat{A}_p = [a_{ij}]$ is Product Inputs into the Process LCA system

$\hat{E}_p = [e_{ij}]$ is the environmental extension matrix of the Process LCA system

$\hat{y}_p$ = This is the functional unit of the Process LCA system

Note:

- ✓ If there are n different types of materials or resources used in producing the product, then the Process LCA system $\hat{A}_p = [a_{ij}]$ will have a dimension of $(n+1)\ x\ (n+1)$.
- ✓ The additional "1" row and column added to the matrix is because the LCA output, is also included in the matrix

Analytical Computation of the Process LCA System, $\hat{A}_p = [a_{ij}]$

$$LCA_p = \hat{E}_p . \hat{A}_p{}^{-1} . \hat{y}_p$$

Let:

- ✓ $\hat{A}_p = [a_{ij}]$ is Product Inputs into the Process LCA system
- ✓ q_i represent the quantity of any inputs, i, into the Process LCA system.

$$\hat{A}_p = [a_{ij}] = \begin{cases} a_{ij} = q_i & if\ i = j\ (and\ i \neq n+1, j \neq n+1) \\ a_{n+1,n+1} = 1 & \\ a_{i,n+1} = -q_i & \forall\ i\ except\ if\ i = n+1 \\ a_{ij} = 0 & if\ i \neq j \end{cases}$$

Reference: Genovese, Acquaye et al (2017)

Analytical Computation of the Process LCA System, $\hat{A}_p = [a_{ij}]$

Assume that in order to produce a 1 kg metal MTL, you require the following five materials: 1.2 kg of Material A, 0.8 kg of material B, 0.2 litres of material C, 0.03 kg of material D and 2.5 kWH of input E a Process LCA system. Construct a Process LCA system in matrix form in the production of the metal MTL.

		PROCESSES					
		Material A	Material B	Material C	Material D	Material E	Output
RESOURCE INPUTS	Material A	1.2	0	0	0	0	-1.2
	Material B	0	1.8	0	0	0	-1.8
	Material C	0	0	0.2	0	0	-0.2
	Material D	0	0	0	0.3	0	-0.3
	Material E	0	0	0	0	0.20	-0.20
	Output	0	0	0	0	0	1

$$\hat{A}_p = [a_{ij}] = \begin{cases} a_{ij} = q_i & if\ i = j\ (and\ i \neq n+1, j \neq n+1) \\ a_{n+1,n+1} = 1 & \\ a_{i,n+1} = -q_i & \forall\, i\ except\ if\ i = n+1 \\ a_{ij} = 0 & if\ i \neq j \end{cases}$$

Example of Constructing Upstream Cut-off: [-U]

		PROCESSES					
		Material A	Material B	Material C	Material D	Material E	Output
RESOURCE INPUTS	Material A	1.2	0	0	0	0	-1.2
	Material B	0	1.8	0	0	0	-1.8
	Material C	0	0	0.2	0	0	-0.2
	Material D	0	0	0	0.3	0	-0.3
	Material E	0	0	0	0	0.20	-0.20
	Output	0	0	0	0	0	1

- ✓ From the above example, 2.5 kWh of Material E was used in the Process LCA system.
- ✓ Assume that the unit price of Material E is £0.08/kWh. As such, the monetary equivalent of material E is 2.5 kWh *£0.08/kWh, which is £0.20.
- ✓ The corresponding I-O sector of Material E is the Electricity Sector, hence, the Technology Matrix of the Electricity sector is multiplied by £0.20 in order to produce a "New" Proportionate Technology Matrix. This is then negated, because the flows are outwards.
- ✓ Set to Zero, all row inputs in the Proportionate Technology Matrix, which are not considered as upstream inputs from the IO LCA system into the Process LCA system.

Setting Up the Input-Output System

- This is similar to the pure Environmental Input-Output LCA system.
- NOTE: If Multi-Regional Input-Output (MRIO) data is available, this must be considered.
- This is because, supply chain inputs into a production system are not limited to inputs from the domestic country, but also from foreign countries

MRIO Framework Analyses

From:

$$\underline{\boldsymbol{x}} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{\boldsymbol{y}}$$

It can be expanded into MRIO framework where:

$$A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix}; y = \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1n} \\ y^{21} & y^{22} & \cdots & y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \cdots & y^{nn} \end{bmatrix}; x = \begin{bmatrix} x^{1} \\ x^{2} \\ \vdots \\ x^{n} \end{bmatrix}$$

- There are $\boldsymbol{n}$ regions
- Dimension of $\boldsymbol{I}$ must be the same as $\boldsymbol{A}$

Interconnecting the Process and I-O LCA Systems

OBJECTIVE: To use supply chain inputs from the Input-Output LCA System as replacements for the truncated inputs, which have been missed in the Process LCA system.

- ✓ The interconnections occurs at the boundaries of the system; referred to as Downstream and Upstream Cut-offs.
- ✓ Downstream Cut-off: flows from the Process LCA system to the Input-Output LCA system. This is generally set to ZERO because it is considered insignificant compared to the much larger Input-Output LCA system
- ✓ Upstream Cut-off: flows from the Input-Output LCA system to the Process LCA system to account for the missing supply chain inputs in the Process LCA. The Upstream Cut-off therefore ensure the LCA system COMPLETENESS.

Constructing Upstream Cut-off: [-U]

- ✓ The negative sign is an indication of the direction of flow (Outflow from the system).
- ✓ **ITERATION PROCESS TO DETERMINE [-U]:**
  - i. Calculate the Monetary Equivalent of each material input into the Process LCA system. This can be done using the unit prices of the inputs as conversion factors since these inputs are in physical quantities.
  - ii. Identify the corresponding I-O sector for each input in the Process LCA system.
  - iii. Using the monetary equivalent evaluated in *(i)*, workout the product of the Technology Matrix and monetary equivalent. This produces the Proportionate Technology Inputs since the Technology Matrix corresponds to 1 unit of Output.
  - iv. Negate the new Proportionate Technology Inputs matrix.
  - v. Set all rows in the combined Proportionate Technology Inputs matrix to zero except inputs considered as upstream inputs that complement the Process LCA system.

Sample Reading Materials

- Acquaye, A. A., Wiedmann, T., Feng, K., Crawford, R. H., Barrett, J., Kuylenstierna, J., ... & McQueen-Mason, S. (2011). Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis. Environmental science & technology, 45(6), 2471-2478.
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Thank You.

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