A Grand Unifying Theory of Hybrid Life-Cycle Assessment

Conference Poster

Author(s):
Weinold, Michael; Majeau-Bettez, Guillaume

Publication date:
2024-05-06

Permanent link:
https://doi.org/10.3929/ethz-b-000668021

A Grand Unifying Theory of Hybrid Life-Cycle Assessment

Michael P. Weinold[1,2]
Guillaume Majeau-Bettez[3]

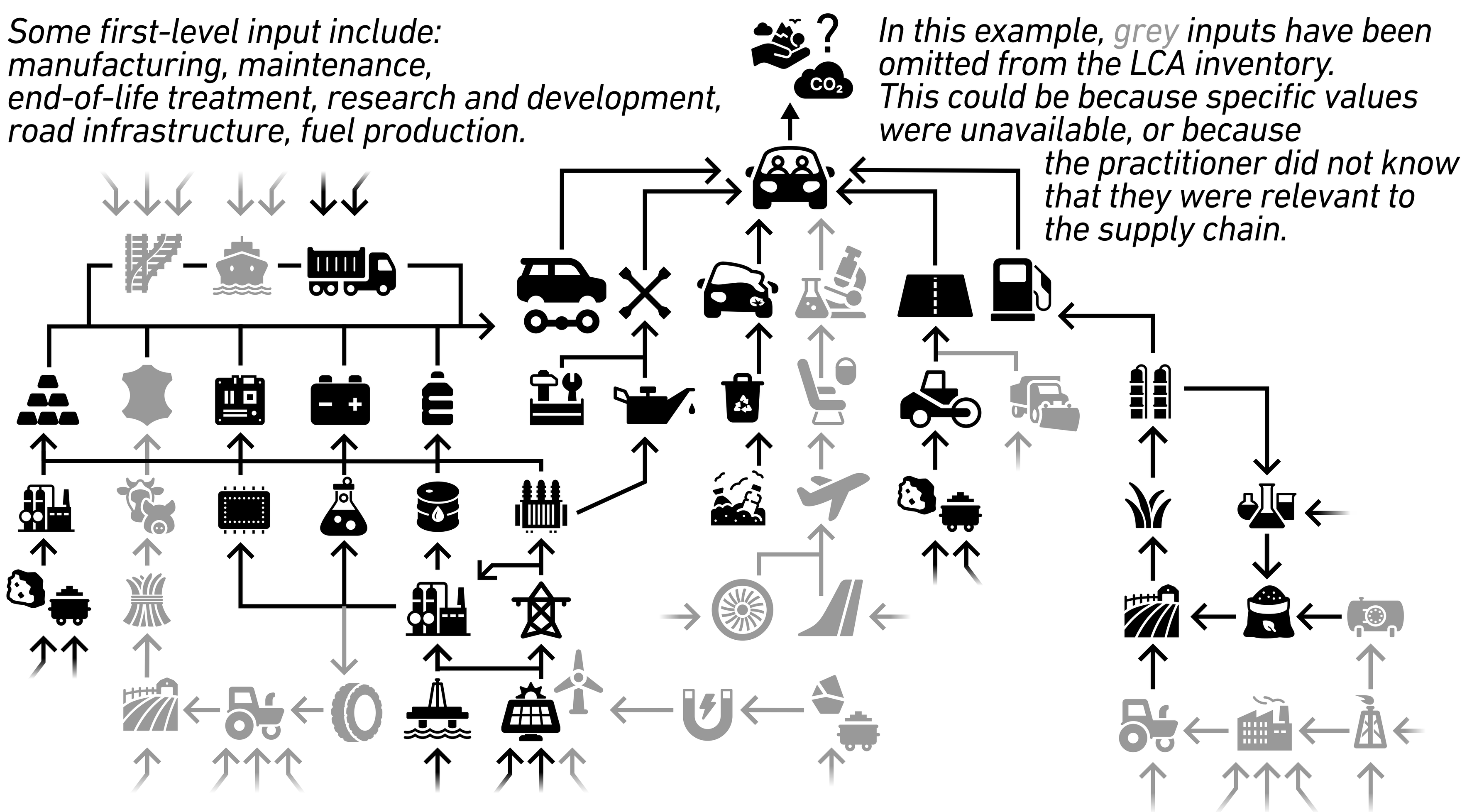
[1]ETH Zurich | Department of Mechanical and Process Engineering
[2]Paul Scherrer Institute | Group for Technology Assessment
[3]Polytechnique Montréal | Department of Chemical Engineering

MOTIVATION

Life-cycle assessment (LCA) is a standardized method to calculate the environmental burdens associated with the production of goods or the provision of services. Obtaining accurate LCA results is no longer a purely academic requirement. The method forms the basis of all environmental impact assessment studies that guide policy decisions about present and future technologies. Even more acutely, LCA results are used to determine the amount of carbon-emission taxes levied on economic activities.

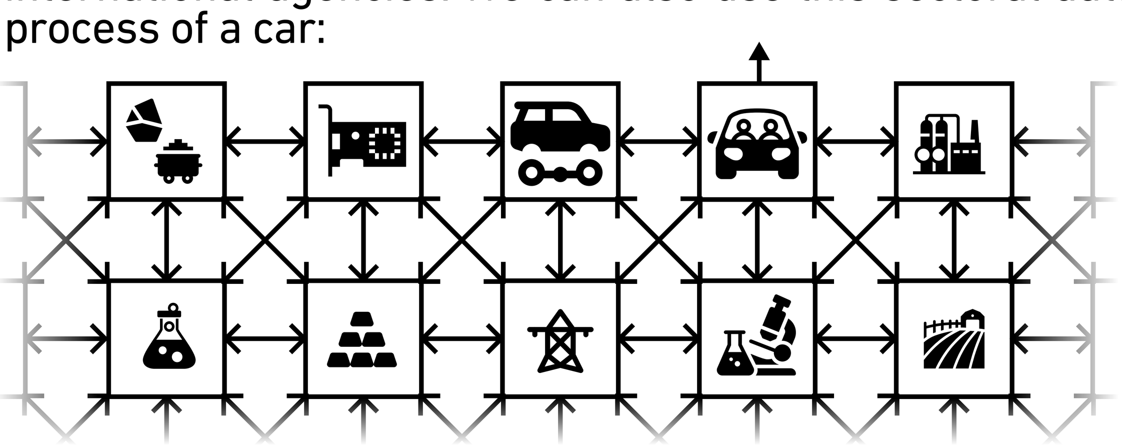
INTRODUCTION

One way to conduct an LCA study of a product or service is to determine the emissions of all relevant upstream production processes [1]. Unfortunately, the complete supply chain of any product is pratically infinite - and often very complex. Production processes often depend on each other in circular patterns. Consider, for instance, the example of a simplified supply chain related to automotive passenger transport with bio-fuels:



As we can see, collecting data on all upstream processes of the supply chain is a monumental task. In general, we can not be sure that we did not miss any relevant inputs.

Another way to conduct an LCA study is to instead use data from "input-output" tables, which quantify the economic (=monetary) flow between different sectors of the economy during one year [2]. These tables are regularly published by national governments and international agencies. We can also use this sectoral data to describe the manufacturing process of a car:



As we can see, sectors are highly aggregated - therefore containing many individual manufacturing processes. However, all sectors together describe the entirety of the economy.

Hybrid LCA (HLCA) is the combination of data from a process inventory (highly detailed, but incomplete) with data from input-output tables (highly aggregated, but complete) to capture the complete effort of the economy associated with production of goods or the

HISTORICAL DEVELOPMENT IN HYBRID LIFE-CYCLE ASSESSMENT

Four different methods for HLCA have historically been recognized in the literature [3]:

The *"tiered"* hybrid method, first proposed by Bullard et al. in 1976/1978 [4] under the term "net energy analysis", simply adds additional demand for the sectoral system. The *"matrix augmentation"* hybrid method, first proposed by Joshi in 1999 [6] connects the process system to the sectoral system, and removes flows already covered by processes. The *"integrated"* hybrid method, first proposed by Suh in 2000/2004 [5] operates in the same way. Finally, the *"path-exchange"* hybrid method, first proposed by Lenzen and Crawford in 2009 [7] changes individual coefficients in the power-series expansion of the A-matrix:

$$\vec{e}_{H(tiered)} = \vec{e}_S + \vec{e}_P = \mathbf{B}_S(\mathbf{I}-\mathbf{A}_S)^{-1}\vec{f}_S + \mathbf{B}_P\mathbf{A}_P^{-1}\vec{f}_P$$

$$\vec{e}_{H(matrix\ augmentation)} = \mathbf{B}_H(\mathbf{I}-\mathbf{A}_H)^{-1}\vec{f}_P$$

$$\vec{e}_{H(integrated)} = \begin{pmatrix}\mathbf{B}_P & 0\\ 0 & \mathbf{B}^*{}_S\end{pmatrix}\begin{pmatrix}\mathbf{A}_P & \mathbf{C}_D\\ \mathbf{C}_U & \mathbf{I}-\mathbf{A}^*{}_S\end{pmatrix}^{-1}\begin{pmatrix}\vec{f}_P\\ 0\end{pmatrix}$$

$$\vec{e}_{H(path-exchange)} = \mathrm{PXC}(\mathbf{B}_S(\mathbf{I}+\mathbf{A}_S+\mathbf{A}_S^2+\mathbf{A}_S^3+\dots))\vec{f}_P$$

Depite a number of recent publications [3], the advantages and drawbacks of these different methods were never conclusively formulated - severely limiting their use.

UNIFYING HYBRID LIFE-CYCLE ASSESSMENT

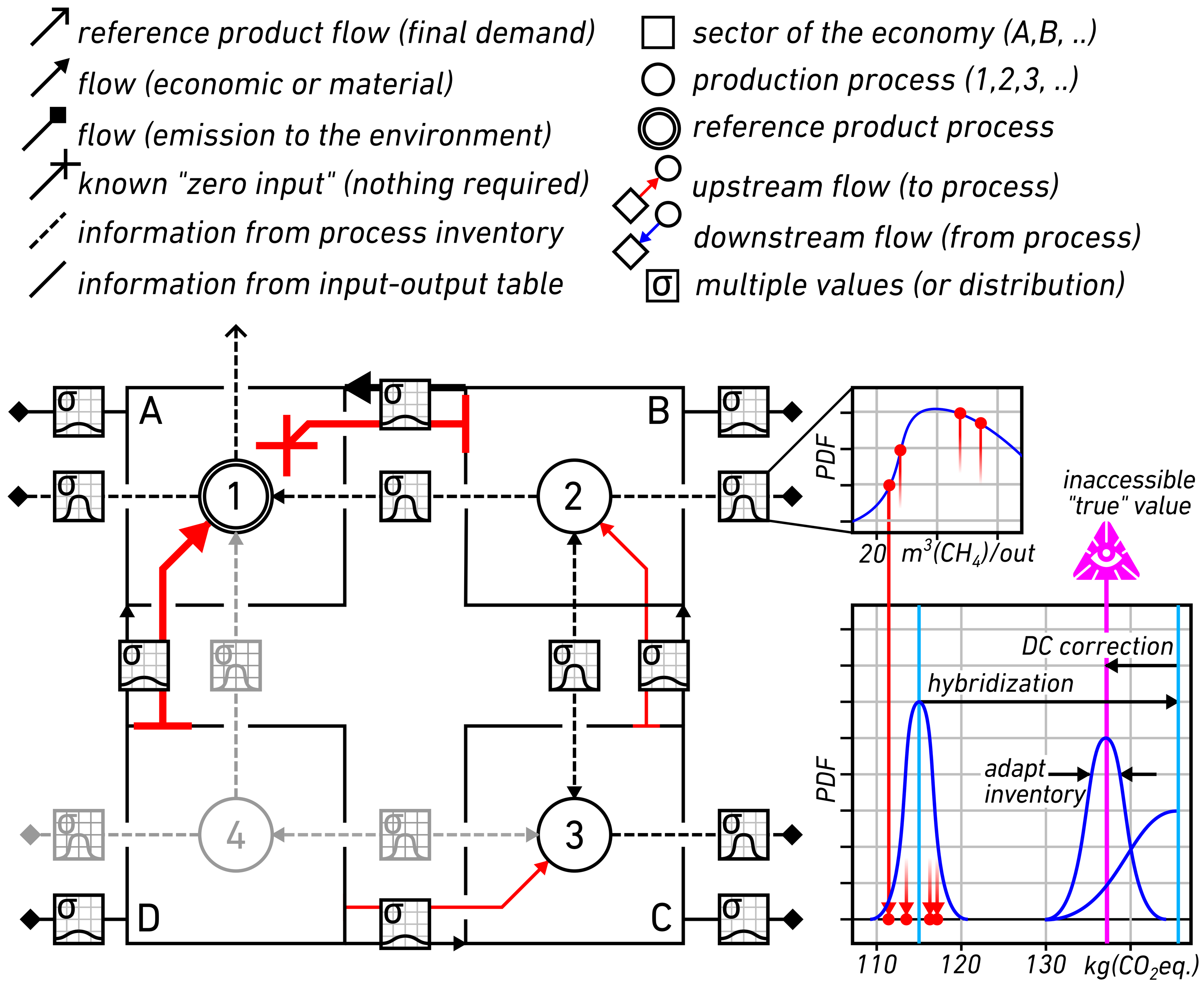
We find that the computational structure of all four HLCA methods is the same. While it had previously been observed (without proof) that the *matrix augmentation* and *integrated* method are "mathematically (...) essentially the same" [8, Sec.2.2.1], no such observation has been made for the other methods. Mathematically, the methods can be described using the equation:

$$\vec{e}_H = \begin{pmatrix}\mathbf{B}_P & 0\\ 0 & \mathbf{B}^*{}_S\end{pmatrix}\begin{pmatrix}\mathbf{A}_P & \mathbf{C}_D\\ \mathbf{C}_U & \mathbf{I}-\mathbf{A}^*{}_S\end{pmatrix}^{-1}\begin{pmatrix}\vec{f}_P\\ 0\end{pmatrix} \qquad \begin{matrix}P\dots\text{process system}\\ S\dots\text{sectoral system}\end{matrix}$$

$\vec{e}_H$ ... environmental burdens
$\mathbf{B}$ ... environmental burden intensity
$\mathbf{A}$ ... technical coefficients
$\mathbf{C}^U$ ... upstream cut-off
$\mathbf{C}^D$ ... downstream cut-off
$\vec{f}$ ... final demand

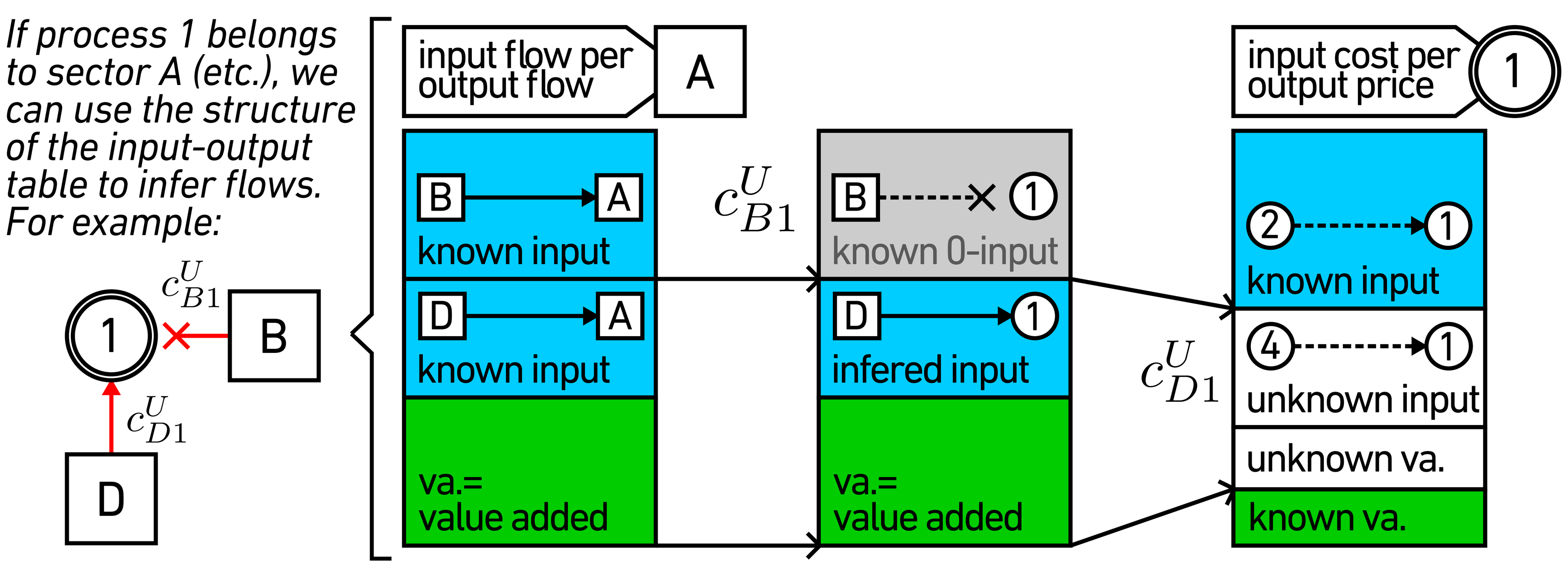
$$b_{ij} = \frac{\text{burden } i}{\text{output } j} \qquad a_{ij} = \frac{\text{flow } i \to j}{\text{output } j} \qquad c_{ij} = \frac{\text{flow } i \to j}{\text{output } j}$$

The four proofs range from "trivial" to "rather involved" and use a basis transformation of the underlying vector space and splitting up indices in the power series expansion of the A-matrix. The way in which this equation describes flows between processes and sectors, can also be illustrated using a novel diagrammatic notation:



This illustrates how upstream flows and downstream flows inter-connect the process system with the sectoral system. Depending on the purpose of the HLCA study, the data origin for the coefficients of the upstream/downstream matrices are different.

If practitoners know how processes are connected to the sectoral system (through sales data for downstream flows and through a bill-of-goods for upstream flows), the matrix can be populated manually. In this case, HLCA is used to solve for "known unknown" inputs. Since that is generally not possible for the background process inventory, these flows can also be infered from the inherent structure of the input-output table [9]. In this case, HLCA is used to solve for "unknown unknown" inputs:



In order to avoid double-counting of flows (and therefore environmental burdens) from both the process system and the sectoral system, monetary balance must be observed:

$$(c^U_{(B-2)1}x_1 + a^P_{21}x_1) + a^S_{(A-1)(B-2)}x_{(A-1)} = a^S_{BA}x_A \qquad x\dots\text{output}$$

REFERENCES

[1] Heijungs and Suh (2002), "The Computational Structure of Life Cycle Assessment", doi: 10.1007/978-94-015-9900-9
[2] Miller and Blair (2021), "Input-Output Analysis: Foundations and Extensions", doi: 10.1017/9781108676212
[3] Crawford et al., Journal of Cleaner Production (2018), "Hybrid life cycle inventory methods – A review", doi: 10.1016/j.jclepro.2017.10.176
[4] Bullard et al., Resources and Energy (1978), "Net energy analysis: Handbook for combining process and input-output analysis", doi: 10.1016/0165-0572(78)90008-7
[5] Joshi, Journal of Industrial Ecology (1999), "Product Environmental Life-Cycle Assessment Using Input-Output Techniques", doi: 10.1162/108819899569449
[6] Suh, Ecological Economics (2004), "Functions, commodities and environmental impacts in an ecological–economic model", doi: 10.1016/j.ecolecon.2003.10.013
[7] Lenzen and Crawford, Environmental Science & Technology (2009), "The Path Exchange Method for Hybrid LCA", doi: 10.1021/es902090z
[8] Peters et al., Ecological Economics (2006), "A comment on "Functions, commodities and environmental impacts in an ecological–economic model"", doi: 10.1016/j.ecolecon.2005.08.008
[9] Strømman and Solli, Journal of Industrial Ecology (2008), "Applying Leontief's Price Model to Estimate Missing Elements in Hybrid Life Cycle Inventories", doi: 10.1111/j.1530-9290.2008.00011.x

This poster was prepared for the SETAC Europe 34th Annual Meeting in Sevilla, Spain (May 2024)
Please address correspondence to: michael.weinold@alumni.ethz.ch

Flagship supported by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Innosuisse – Swiss Innovation Agency