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RESEARCH AND ANALYSIS

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Lifting the veil on the correction of double counting incidents in hybrid life cycle assessment

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Abstract

Life cycle assessment (LCA) and environmentally extended input–output analyses (EEIOA) are two techniques commonly used to assess environmental impacts of an activity/product. Their strengths and weaknesses are complementary, and they are thus regularly combined to obtain hybrid LCAs. A number of approaches in hybrid LCA exist, which leads to different results. One of the differences is the method used to ensure that mixed LCA and EEIOA data do not overlap, which is referred to as correction for double counting. This aspect of hybrid LCA is often ignored in reports of hybrid assessments and no comprehensive study has been carried out on it. This article strives to list, compare, and analyze the different existing methods for the correction of double counting. We first harmonize the definitions of the existing correction methods and express them in a common notation, before introducing a streamlined variant. We then compare their respective assumptions and limitations. We discuss the loss of specific information regarding the studied activity/product and the loss of coherent financial representation caused by some of the correction methods. This analysis clarifies which techniques are most applicable to different tasks, from hybridizing individual LCA processes to integrating complete databases. We finally conclude by giving recommendations for future hybrid analyses.

KEYWORDS

data quality, environmental input–output analysis, hybrid life-cycle assessment, industrial ecology, life cycle assessment (LCA), life cycle inventory (LCI)

1 | INTRODUCTION

Both life cycle assessment (LCA) and environmentally extended input–output analyses (EEIOA) allow the quantification of emissions linked directly or indirectly to a product's production, use, and end-of-life, which then enlightens the environmentally friendlier choice between competing products (Jeswani, Azapagic, Schepelmann, & Ritthoff, 2010). Even if their goal is the same, the methods do not operate in the same way. LCA aims at providing detailed descriptions of every process involved in the life cycle of a studied activity (International Organization for Standardization, 2006), while EEIOA regroups national inventories to describe the interdependence between economic sectors (Miller & Blair, 2009).

The determination of the life cycle inventory (LCI) according to ISO standards requires the description of all processes linked by the economic flows to the provision of a functional unit, along with all elementary flows that describe the exchanges of these processes with the environment (International Organization for Standardization, 2006). However, the economy is so deeply intertwined that it could be considered to be almost involved in its entirety in the life cycle of every single product (Gibon & Schaubroeck, 2017; Pomponi & Lenzen, 2017). Such broad coverage and inventory collection is currently impossible to achieve given the level of detail that is required in LCA and LCA practitioners strive to communicate the limited coverage of their studies by the definition of explicit system boundaries (Suh et al., 2004). System boundaries and coverage are not uniform and largely depend on data availability and research resources, complicating comparison between studies (Price & Kendall, 2012). Even harmonized databases struggle to ensure consistent coverage in process descriptions (Mongelli, Suh, & Huppes, 2005). In addition, the collection and use of data on services has always been a shortcoming in LCA, as can be shown by the underrepresentation of services in databases such as ecoinvent (Wernet et al., 2016). The data collection in LCA is therefore *never* complete since multiple inputs (deemed negligible or unavailable) are necessarily ignored. These missing inputs can either result from an omission of an input (e.g., no data available on the IT services required to craft a car) or from an underestimated requirement in the inventory (e.g., steel is accounted for in the inventory but is incomplete because bolts of steel were ignored). While an individual omission or underestimation may or may not impact the results of an LCA, the same cannot be ascertained for these omissions together which trigger what is referred to as truncations in LCA. Estimates of these truncations in the literature typically ranged from 20% to 50% (Ferrao & Nhambiu, 2009; Junnila, 2006; Lenzen, 2000; Lenzen & Dey, 2000; Norris, 2002; Rowley, Lundie, & Peters, 2009). The truncation of services alone is estimated to cause a systematic average underestimation of 6% (Ward, Wenz, Steckel, & Minx, 2017). Truncation errors in LCA are often being debated. Recently Yang, Heijungs, and Brandão (2017) argued that truncation errors in LCA could be lower than aggregation errors in IO, which was disputed by Pomponi and Lenzen (2017). Another common argument against the problem of truncations in LCA is that in a context of comparative studies, truncations between two similar products, which thus share similar value chains, should be similar themselves. Truncations would therefore not be a hindrance in comparative LCAs. While this is generally true, there are multiple cases where commodities that differ and rely on different value chains can fulfill a similar function, and in such cases LCA comparison results can switch, as proved in (Lenzen & Treloar, 2003).

EEIOA comes from the economic input–output (IO) models, first developed by Leontief (Leontief, 1936) to capture indirect links between household consumption and employment and later extended to encompass waste flows and exchanges with the environment (Leontief, 1970). It is based on trading information that companies provide to their government, which result in national inventories (European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank, 2009). The information is then compiled into a technology matrix (A) that gives average production functions (recipes) at sectoral level. For instance, the French industry of automobiles requires €0.0257 of commodities from the French steel industry and €0.0024 of commodities from the French electricity industry, and so forth to produce €1 of its products (Wood et al., 2015). These national input–output tables can be combined to obtain a global representation of the world economy as a multiregional input–output (MRIO) table (Andrew & Peters, 2013; Lenzen, Moran, Kanemoto, & Geschke, 2013; Stadler et al., 2018; Tukker & Dietzenbacher, 2013). These tables being based on national accounts, they include every declared monetary transaction. As such, there are no problems of truncations for formal economic flows of an EEIOA (Lenzen, 2000); every value chain is captured in its entirety. It has to be noted though that informal economy is not captured by EEIOA (e.g., voluntary work, smuggling, self-employed people) and that satellite environmental emissions and resource extraction accounts may also have limited coverage. The downside of EEIOA is that the recipes are heavily aggregated, representing the average production of group of products rather than the manufacture of a specific product, notably to protect the secrets of individual companies. Consequently, an electric car and a diesel car can (depending on the IO table used) be included in a same product group (“Motor vehicles”) and would therefore have the same impact on the environment. It is therefore impossible to realize a study on a *specific* product using EEIOA alone (Suh et al., 2004).

LCA and EEIOA both have respective strengths and weaknesses: LCA can study specific products but suffers from truncations and inconsistent boundary definitions, whereas EEIOA has complete system boundaries (no truncations) but can only access information at the sectoral level. It is apparent that these techniques are complementary and they were thus combined into hybrid life cycle assessments (HLCA) to obtain the best out of both methods. HLCA has been a focus of research for decades (Bullard & Penner, 1978; Joshi, 1999; Lenzen & Crawford, 2009; Moskowitz & Rowe, 1985; Nakamura & Kondo, 2002; Suh & Huppes, 2005).

By mixing LCA and EEIOA data to obtain a specific and complete inventory, HLCA requires to control that: (1) no data are *truncated*, meaning that all flows must be represented either by LCA or by EEIOA, (2) no data are *double counted*, meaning that all data of an inventory must be inventoried *only once* either by the LCA or by the EEIOA (i.e., a same input cannot be accounted for by both LCA and EEIOA at the same time). This control, which the hybrid community refers to as “correction for double counting” is an important part of the hybridization of an inventory. It is also complicated by the differences in aggregation level, measurement units (physical units used in LCA, monetary units used in EEIOA) and scope of LCA and EEIOA datasets. Many methods have been developed to tackle these issues, but these methods were created by isolated groups of scientists in the context of different studies with different purposes. It results in methods to correct double counting that require different amount of knowledge on the data used and that work with different assumptions, which ultimately leads to different results of hybridization. Despite being the source of differences in results, these methods have never been the focus of any study and as such, have never been systematically analyzed, compared, or even inventoried. Moreover, the hybrid community which was until recently solely focused on the hybridization of individual processes, is now looking toward massive hybridization, ultimately resulting in hybrid databases (Crawford, Bontinck, Stephan, Wiedmann, & Yu, 2018; Stephan, Crawford, & Bontinck, 2018; Strømman, Peters, & Hertwich, 2009; Suh & Lippiatt, 2012; Weidema, 2011). To achieve this overarching goal, the methods to correct double counting must be streamlined for application to a large number of processes about which less information is available (because the hybrid practitioner is not the one who collected the data).

2 | AIM AND SCOPE

The present paper aims at reviewing and harmonizing the existing double counting correction techniques—their assumptions, limitations, efficiency, applicability to database hybridization, and effects on hybridization results—and addressing some of their shortcomings through the development of two novel methods. All the methods will be introduced following the same example to allow direct comparisons and represented with matrices in a common notation (when possible) in order to better understand their functioning and differences.

The article first introduces the mathematical frameworks of LCA, EEIOA, and HLCA with which we operate. We then introduce the example on which all methods will be applied. We continue by presenting the different double counting correction techniques and exposing their assumptions and limitations, resulting in a diagram that maps out the relationships between these models. We then discuss on inconsistencies brought about by some of the methods. Finally, we provide recommendations for future hybrid analyses on key data to include in the data collection process, as well as which correcting method to apply in which situation.

The article is focused on problems of double counting applied to hybridization of single products. It does not tackle issues related to double counting in the responsibility sharing between LCA processes (see Gallego & Lenzen, 2005) or concept of total flow (see Szyrmer, 1992). This article also does not introduce the different scopes of hybridization (tiered hybrid, matrix augmentation, integrated hybrid, waste IO, and path exchange) but fully focuses on the methods to correct for double counting (see Crawford et al., 2018 and Suh & Huppes, 2005). The matrix notation and the structure of the hybrid technology matrix employed throughout this article are not novel and do not constitute an original contribution of this study (Perkins & Suh, 2019; Strømman et al., 2009). Our analysis of the double counting correction techniques is generally applicable to all hybridization scopes, because they all share the common challenge of harmonizing the boundaries between LCA and EEIOA inventories, as demonstrated in Supporting Information S1. This study focuses on the use of EEIOA as complement to LCA process data (i.e., upstream cut-offs) and does not address the disaggregation of EEIOA product groups with LCA data (i.e., downstream cut-offs). Finally, this study only concerns HLCAs relying on EEIOA to estimate missing inputs to processes, see Section 3.1.

3 | HYBRID LCA

3.1 | An important distinction between two different uses of EEIOA data in hybrid analyses

To clarify how and why the need to correct for instances of double-counting arises, we must first distinguish between two conceptually distinct uses of EEIOA data in hybrid LCAs, each solving a particular problem. In other words, while all hybrid LCAs rely on EEIOA as a complementary source of data, the types of data gaps that are filled by this complement differ across studies.

In some HLCAs, EEIOA tables are used more or less like any other generic ("background") LCA database: they are used to model the flows upstream in the value chain of an inventoried (i.e., known) product flow of the system under investigation. Thus, a practitioner collects primary data to inventory the flows of a given ("foreground") unit process, and some of these flows may then be modeled as provided by another LCA process (e.g., from ecoinvent), or they may be modeled as being provided by a corresponding EEIOA sector. For example, in Figure 1a, the practitioner identifies input flows of steel, electricity, and IT services. While the production of the first two are readily described by LCA processes (boxes in light gray), the delivery of IT services may prove difficult to inventory and may thus be unavailable in LCA databases. Relying instead on an average IO sector description for the provision of IT services allows the analyst to describe the value chain of this known input flow (boxes in dark gray). In short,

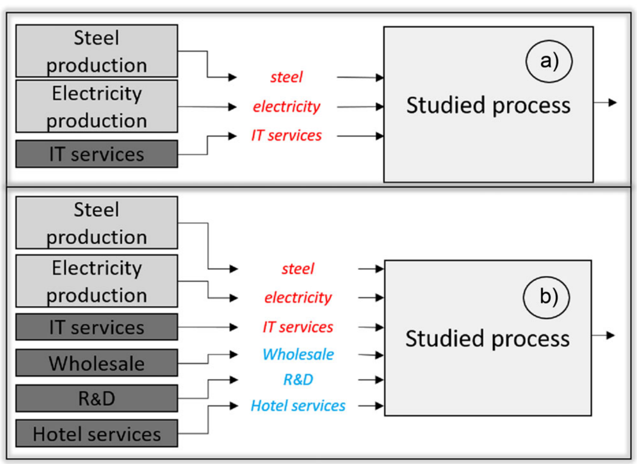


FIGURE 1 Example showing two ways EEIOA data can be used in hybrid analyses. In (a), the practitioner inventoried three inputs (in red), of which one is not inventoried in general LCA database (boxes in light gray) and is thus represented by IO (boxes in dark gray). The sum of the cost of these three inputs + value-added amounts to the production cost of the studied process. In (b), that sum is smaller than the production cost. There are thus missing inputs, which are (in this case) estimated (in blue) based on the IO data structure of the corresponding sector

since all sectors of the economy are present in an EEIOA database, an approximate upstream value chain description can always be found for any inventoried input flow, and these flows no longer need to be excluded from the system boundary due to lack of upstream data, as exemplified in Fernández-Dacosta et al. (2017),[1] Gibon et al. (2015),[2] and Suh (2004)[3].

In contrast, some other HLCAs rely on EEIOA sector descriptions to estimate any potentially remaining missing direct inputs flows of an LCA process. In the example Figure 1b, if the LCA practitioner is not confident that the three inventoried inputs (in red) constitute the totality of the requirements of the process, any missing inputs, for example, wholesale trade, research, and development, and hotel services (Figure 1b, in blue), may be estimated based on the requirements of similar processes aggregated in the corresponding EEIOA sector. Arvesen & Hertwich (2011)[4], Perkins & Suh (2019)[5], and Strømman et al. (2009)[6] all explicitly rely on this strategy.

The first use is especially appropriate if the practitioner is confident that he or she had access to all direct inputs to the LCA process, notably if the sum of the cost of these inputs and value-added leads to complete cost coverage. Otherwise, there is a high risk that some input flows have been ignored, and that environmental burdens are still underestimated. The second use strives to fill this remaining data gap to correct for this negative bias. In doing this, care must be taken to avoid any overlap between the primary data and these new highly aggregated input estimates, which would lead to a positive bias, hence the need to correct for double-counting.

As this need to ensure no overlap between LCA and EEIOA only arises with the second usage, it will be the sole focus of our article. Throughout the following analysis, it should be kept in mind that the attempt is to estimate missing direct input flows of a process (and associated lifecycle requirements) where further primary data collection proved infeasible.

Of course, the above distinction between the two uses of EEIOA data is purely conceptual. In practice, these can be combined. Furthermore, although we have never encountered this in the literature, it would be possible to use EEIOA tables to only determine the quantity of the missing flows (blue inputs) without relying on these tables to represent these flows' upstream value chains. The upstream value chains of these additional flows could then be modeled through other data sources (e.g., the LCA database itself, if an appropriate process is available). Here, modeling upstream value chains with EEIOA or another source has no implication on the focus of this article, that is, on the correction for the double counting, refer to Supporting Information S1.

3.2 | What is double counting?

Hybridization mixes LCA and EEIOA system descriptions to obtain specificity and completeness. Unit process inventories from LCA are therefore completed with IO complements, that is, an estimate of what was deemed missing in the original LCA inventory (see Equation (1)).

$$\text{All inputs} = \text{LCA inputs} + \underbrace{\text{estimates of missing inputs}}_{\textit{IO complements}} \tag{1}$$

When estimating the missing inputs of a given LCA process using EEIOA, we (1) identify the equivalent EEIOA production function and all its inputs, but (2) we only keep the inputs that do not overlap with the flows already inventoried in the foreground. This means that, for the sake of this analysis, the hybridization described in Equation (1) can be conceptually split into two formal steps. First, all the requirements of the corresponding EEIOA production function are added to the incomplete LCA production function we wish to hybridize. This step complements the missing inputs, but necessarily (and explicitly) represents twice the inputs originally present in the LCA inventory. As a second conceptual step, these excessive inputs are removed to avoid double-counting, hence the name "correction for double counting" in the literature (Strømman et al., 2009) (see Equation (2)).

$$\text{All inputs} = \underbrace{(\text{LCA inputs} + \text{all EEIOA inputs})}_{\textit{uncorrected hybridization}} - \underbrace{\text{overlapping inputs}}_{\textit{correction}} \tag{2}$$

By definition, these two conceptual substeps can equivalently be performed in one step, where EEIOA inputs are corrected and added to LCA inputs, but, for clarity, and because this article focuses on this second conceptual step, we will systematically present them as distinct. To explore correction for double counting, we first show the double counting, and then we show the (various forms of) correction. For example, the hybridization of a process "production of a car" will include after the first step, inputs of services and of steel from the average production of a vehicle

[1] "The 2011 dataset from the EXIOBASE 3.3 environmentally extended, multi-regional supply-use/input-output database was used to model the economic background for infrastructure of some SAs for hybrid modelling."

[2] "In a hybrid LCA, the foreground system typically requires both physical inputs from the process LCI database and economic inputs from the input–output database."

[3] "The upstream cut-off by processes matrix is derived by dividing the total bill of goods for the inputs that are not covered by a processes in a process-based system during the period of steady-state approximation by the total unit operation time of each process."

[4] "The foreground processes are assigned the same input distributions as their belonging IO sector."

[5] "[...] the "management of companies and enterprises" commodity was not already included in the process LCA and so was added *using input-output data* during the hybridization."

[6] "To achieve a more robust inventory compilation procedure we require *all* the available data on monetary inputs."

TABLE 1 Notations used throughout this article

Symbol	Coefficient	Description
$\boldsymbol{m}, \boldsymbol{n}, \boldsymbol{k}$		LCA products or processes (e.g., pump, stainless steel/production of pump, production of stainless steel)
$\boldsymbol{M}, \boldsymbol{N}, \boldsymbol{K}$		EEIO product groups (e.g., Machinery, Steel)
$\mathcal{M}, \mathcal{K}$		STAM categories of product groups which share similar physical descriptions (e.g., Machines, Metals)
$\mathcal{F}$		STAM categories of product groups which share similar functionalities (e.g., Liquid Fuels)
$\boldsymbol{I}$		Identity matrix
$\boldsymbol{A}^{lca}$	a_{mk}^{lca}	LCA technology matrix
$\boldsymbol{B}^{lca}$	b_{mk}^{lca}	LCA environmental extensions matrix
$\boldsymbol{y}^{lca}$	y_k^{lca}	LCA functional unit vector
$\boldsymbol{q}^{lca}$	q_k^{lca}	LCA vector of total environmental interventions
$\boldsymbol{A}^{io}$	a_{MK}^{io}	EEIO technology matrix
$\boldsymbol{B}^{io}$	b_{MK}^{io}	EEIO environmental extensions matrix
$\boldsymbol{y}^{io}$	y_K^{io}	EEIO final demand vector
$\boldsymbol{q}^{io}$	q_K^{io}	EEIO vector of total environmental interventions
$\boldsymbol{q}^{hyb}$	q_K^{hyb}	Hybrid vector of total environmental interventions
$\boldsymbol{C}^{u}$		Upstream complement matrix
	$c_{Mk}^{uncorrected}$	Uncorrected coefficient of the upstream complement matrix
	c_{Mk}^{binary}	Coefficient of the upstream complement matrix corrected using the binary method
	c_{Mk}^{SSM}	Coefficient of the upstream complement matrix corrected using the SSM
	c_{Mk}^{BPC}	Coefficient of the upstream complement matrix corrected using the BPC
	c_{Mk}^{STAM}	Coefficient of the upstream complement matrix corrected using the STAM
$\boldsymbol{C}^{d}$	c_{mK}^{d}	Downstream complement matrix
$\boldsymbol{H}$	h_{Kk}	Concordance matrix product group/product
$\mathbf{G}$	$g_{M\mathcal{M}}$	Concordance matrix category/product group
$\boldsymbol{\pi}$	π_k	Vector of prices for LCA products
$\boldsymbol{\Lambda}$	λ_{Mk}	Binary filter matrix
$\boldsymbol{\Theta}$	θ_{Mk}	SSM filter matrix
$\boldsymbol{\Gamma}$	$\gamma_{\mathcal{M}\mathcal{K}}$	STAM filter matrix
$\boldsymbol{\Phi}$	φ_{Mk}	STAM filter matrix
$= 0^*$		Real zero in the inventory (i.e., zero coming from the specificity of the inventory and not because of the unavailability of data)

according to EEIOA. While the introduction of services data is welcome because the original inventory poorly considered them, inputs such as steel were already included in the original inventory. The inputs of steel are thus accounted for twice in the resulting hybrid inventory, which leads to an overestimation if left uncorrected.

3.3 | Mathematical framework

The results of hybridization will be described using matrices. As such, we need to introduce LCA's, EEIOA's, and HLCA's mathematical frameworks. LCA and EEIOA use different conventions as to how to represent their respective technology matrices. Throughout the article we chose to use EEIOA's convention, but at any point in the article one can switch to LCA's convention[7]. See Table 1 for a summary of the different notations of this article.

LCA's mathematical framework has been formalized by Heijungs and Suh (2002) and is (using EEIOA's convention) as follows:

$$\boldsymbol{q}^{lca} = \boldsymbol{B}^{lca} \cdot \left(\boldsymbol{I} - \boldsymbol{A}^{lca}\right)^{-1} \cdot \boldsymbol{y}^{lca} \tag{3}$$

[7] To pass from EEIOA to LCA notations, use the relationship $\boldsymbol{T} = (\boldsymbol{I} - \boldsymbol{A})$ where $\boldsymbol{T}$ corresponds to the technology matrix using LCA's convention, $\boldsymbol{I}$ is the identity matrix and $\boldsymbol{A}$ corresponds to the technology matrix from EEIOA's convention.

where vector $\boldsymbol{y}^{lca}$ contains the functional unit, matrix $\boldsymbol{A}^{lca}$ is the technological matrix defining the amount of technological inputs per process, matrix $\boldsymbol{B}^{lca}$ contains the different environmental interventions per process and vector $\boldsymbol{q}^{lca}$ quantifies the total environmental interventions linked to the functional unit over the whole life cycle.

EEIOA is based on the famous Leontief's equation (Leontief, 1936) from Input–Output:

$$\boldsymbol{x} = \left(\boldsymbol{I} - \boldsymbol{A}^{io}\right)^{-1} \cdot \boldsymbol{y}^{io} \tag{4}$$

in which $\boldsymbol{x}$ is the total output of the economy, $\boldsymbol{A}^{io}$ the technological matrix and $\boldsymbol{y}^{io}$ the final demand.

Environmental extensions have then been included to transform Equation (4) as follows (Leontief, 1970):

$$\boldsymbol{q}^{io} = \boldsymbol{B}^{io} \cdot \left(\boldsymbol{I} - \boldsymbol{A}^{io}\right)^{-1} \cdot \boldsymbol{y}^{io} \tag{5}$$

in which $\boldsymbol{y}^{io}$ is the final demand, $\boldsymbol{A}^{io}$ is the technology matrix, $\boldsymbol{B}^{io}$ is the matrix of the environmental burdens (thus "environmentally extended") and $\boldsymbol{q}^{io}$ corresponds to the total emissions linked to the final demand.

It results that hybrid LCA follows the next Equation (6) (Crawford et al., 2018):

$$\boldsymbol{q}^{hyb} = \left[\boldsymbol{B}^{lca}\ \boldsymbol{B}^{io}\right] \cdot \left(\boldsymbol{I} - \begin{bmatrix} \boldsymbol{A}^{lca} & \boldsymbol{C}^{d} \\ \boldsymbol{C}^{u} & \boldsymbol{A}^{io} \end{bmatrix}\right)^{-1} \cdot \begin{pmatrix} \boldsymbol{y}^{lca} \\ 0 \end{pmatrix} \tag{6}$$

where $\boldsymbol{y}^{lca}$ corresponds to the functional unit of the system to hybridize, $\boldsymbol{A}^{lca}$ and $\boldsymbol{A}^{io}$ are the technology matrices for LCA and EEIOA respectively, $\boldsymbol{C}^{u}$ contains the upstream IO complements (often also called upstream cut-off matrix (Suh, 2004), $\boldsymbol{C}^{d}$ corresponds to the downstream complements (i.e., the use of LCA inventoried commodities within the rest of the economy; often set to zero), $\boldsymbol{B}^{lca}$ and $\boldsymbol{B}^{io}$ represent the environmental interventions linked to the LCA and EEIOA parts of the hybrid system and $\boldsymbol{q}^{hyb}$ gives the total emissions linked to the hybrid inventory.

The determination of the inputs of $\boldsymbol{C}^{u}$ is not defined in an equation to the best of the authors' knowledge. This determination was extensively described in the literature however (Strømman & Solli, 2008; Strømman et al., 2009; Yu & Wiedmann, 2018) and can accordingly be translated into the following equation (where $c^{uncorrected}$ are coefficients of $\boldsymbol{C}^{u}$ prior to correcting for double-counting):

$$c_{Mk}^{uncorrected} = a_{MK}^{io} \cdot h_{Kk} \cdot \pi_{k} \tag{7}$$

The EEIOA requirement of product group M for the production of product group K (a_{MK}^{io}) is multiplied by the coefficient of the concordance matrix matching LCA process k to its corresponding product group K (h_{Kk}) and by the price of product k (π_k). This gives the uncorrected upstream cut-off coefficient ($c_{Mk}^{uncorrected}$), complementing process k with data on product group M, which has to be corrected to avoid potential overestimation. Refer to Supporting Information S2 for a demonstration of the determination of uncorrected upstream cut-offs.

4 | CORRECTING FOR DOUBLE COUNTING

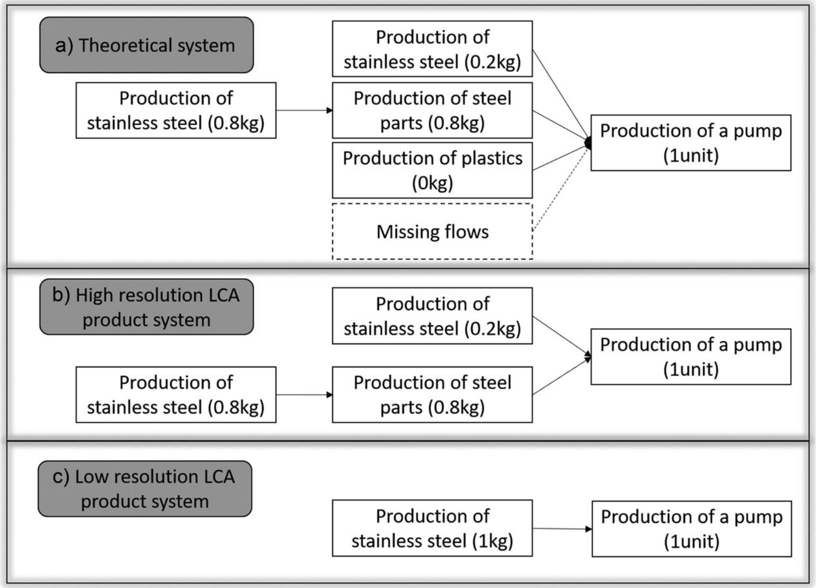
4.1 | Introduction of the example

The methods to correct for double counting will be introduced through an example: the production of a pump. The simplified production of this fictional pump relies on 0.2 kg of stainless steel and 0.8 kg of prefabricated parts composed of the same stainless steel. Let it be a given that the production of this pump does not require any kind of plastics and that the process description is incomplete thus requiring to be complemented through hybridization (Figure 2a).

Figure 2b shows how LCA would represent the production of the fictional pump. Missing flows are obviously not explicitly in the product system and the null inputs are typically not entered explicitly either. As a result, the information according to which the production of the pump does not require any inputs of plastics is not seen in an LCA product system. Moreover, the fact that the parts are prefabricated is often either unknown or ignored depending on the resolution. Using a low-resolution product system can result in an aggregation of steel and steel parts into steel only (Figure 2c). Despite the difference, both systems represented in Figures 2b and 2c would yield identical LCA estimates of exchanges with the environment. In order to expose some of the shortcomings of the different methods to correct for double counting, we will consider having a low-resolution product system (Figure 2c).

In Figure 3, the hybrid technology matrix is represented, with $\boldsymbol{A}^{lca}$ containing the LCA data on the production of the pump, $\boldsymbol{A}^{io}$ is the commodity-by-commodity technology matrix with EEIOA data (inspired from Exiobase, Wood et al., 2015), $\boldsymbol{C}^{u}$ and $\boldsymbol{C}^{d}$ are empty for now because the system is not yet hybridized. The production of stainless steel and plastics has no impact on the hybridization of the pump, and their values are therefore omitted and simply denoted by "n" for number.

FIGURE 2 A same system can be represented with different resolutions in product systems and lose information as a result



The inventory of the production of the pump is truncated since there are missing or incomplete inputs, we thus hybridize this process. We assess that it belongs to the Machinery product group (through a concordance matrix $\boldsymbol{H}$) and the fictional price of the pump ($\pi = 12$€/unit) is then used to convert the EEIOA data (from Machinery) into $\boldsymbol{C}^u$ coefficients. Figure 4 represents this first step, thus resulting in an uncorrected hybrid system. Notice that the steel constituting the pump is inventoried both by LCA and EEIOA: it is therefore double counted which thus requires correction.

4.2 | Existing methods to correct for double counting

4.2.1 | Binary method

The first identified method has been regularly used in several hybrid LCAs without ever being named (Arvesen & Hertwich, 2011; Arvesen, Birkeland, & Hertwich, 2013; Deng, Babbitt, & Williams, 2011; Lin, Liu, Meng, Cui, & Xu, 2013; Stephan et al., 2018; Wiedmann et al., 2011). Given its nature, we chose to refer to it as the *binary method*. The method consists in inserting a matrix ($\boldsymbol{\Lambda}$) into Equation (7), containing information on which inputs are explicitly covered by LCA or not, essentially filtering which EEIOA inputs to set to zero in the uncorrected upstream cut-off matrix, resulting in the (binary) corrected upstream complement matrix ($\boldsymbol{C}^u$), whose coefficients are determined following Equation (8).

$$c_{Mk}^{binary} = \lambda_{Mk} \cdot a_{MK}^{io} \cdot h_{Kk} \cdot \pi_k \tag{8}$$

$$c_{Mk}^{binary} = \lambda_{Mk} \cdot c_{Mk}^{uncorrected} \tag{8'}$$

The determination of the coefficients of $\boldsymbol{\Lambda}$ works as follows: whenever any input (m) is explicitly included into the process-based inventory ($a_{mk}^{lca} \neq 0$), the coefficient of its corresponding product group (M, where $m \in M$) will be forced to zero ($\lambda_{Mk} = 0$). As more than one LCA product can be matched to an EEIOA product group, a summation term is included in Equation (9) to ensure that the EEIOA complement is set to zero whenever *any m* element of *M* is found in the LCA inventory.

$$\lambda_{Mk} = \begin{cases} 0 & \text{if } \sum_{m \in M} a_{mk}^{lca} \neq 0 \\ 1 & \text{if } \sum_{m \in M} a_{mk}^{lca} = 0 \end{cases}, \quad \{\forall M, k \tag{9}$$

In our example, the input coefficient from the steel product group (M) is forced to zero, because the process-based inventory already explicitly includes 1 kg of stainless steel (m); all the EEIOA complements from other product groups are kept (Figure 5a).

4.2.2 | Strømman and Solli's method

The second identified method was developed by Strømman and Solli (2008) but was not named. Strømman and Solli's method (SSM hereafter) is similar to the binary method, in the sense that it also forces to zero all of the inputs from product groups whose products are explicitly included in the process-based inventory. The difference between the two methods comes from the introduction of another matrix (called theta) which allows

	Production of: Pump (unit)	Production of: Stainless steel (kg)	Production of: Plastics (kg)	Machinery (€)	Steel (€)	Fabricated metal (€)	Plastic (€)	Diesel (€)	Lubricant (€)	Other (€)
Pump (unit)	0	n	n	0	0	0	0	0	0	0
Stainless steel (kg)	1	n	n	0	0	0	0	0	0	0
Plastics (kg)	0	n	n	0	0	0	0	0	0	0
Machinery (€)	0	n	n	0.07	0.02	0.01	0.01	0.003	0.003	0.01
Steel (€)	0	n	n	0.03	0.2	0.1	0	0	0	0.006
Fabricated metal (€)	0	n	n	0.07	0.02	0.085	0.01	0.004	0.004	0.01
Plastic (€)	0	n	n	0.001	0	0.001	0.001	0	0	0.01
Diesel (€)	0	n	n	0.001	0	0	0	0	0	0
Lubricant (€)	0	n	n	0.001	0.002	0	0	0	0	0
Other (€)	0	n	n	0.4003	0.4755	0.5583	0.7922	0.7022	0.7098	0.621
Added value (€)	0	n	n	0.4577	0.2825	0.2457	0.1868	0.2908	0.2832	0.343
CO_2 (kg)	0.1	n	n	0.064	1.651	0.073	0.063	1.018	0.984	0.356

A^{lca} C^{d} C^{u} A^{io}

FIGURE 3 Representation of the hybrid system, prehybridization (A^{lca} = LCA technology matrix, A^{io} = EEIOA commodity-by-commodity technology matrix, C^{u} = upstream complements, C^{d} = downstream complements)

	Production of: Pump (unit)	Production of: Stainless steel (kg)	Production of: Plastics (kg)	Machinery (€)	Steel (€)	Fabricated metal (€)	Plastic (€)	Diesel (€)	Lubricant (€)	Other (€)
Pump (unit)	0	n	n	0	0	0	0	0	0	0
Stainless steel (kg)	1	n	n	0	0	0	0	0	0	0
Plastics (kg)	0	n	n	0	0	0	0	0	0	0
Machinery (€)	0.84	n	n	0.07	0.02	0.01	0.01	0.003	0.003	0.01
Steel (€)	0.36	n	n	0.03	0.2	0.1	0	0	0	0.006
Fabricated metal (€)	0.84	n	n	0.07	0.02	0.085	0.01	0.004	0.004	0.01
Plastic (€)	0.012			0.001	0	0.001	0.001	0	0	0.01
Diesel (€)	0.012			0.001	0	0	0	0	0	0
Lubricant (€)	0.012	n	n	0.001	0.002	0	0	0	0	0
Other (€)	4.8036	n	n	0.4003	0.4755	0.5583	0.7922	0.7022	0.7098	0.621
Added value (€)	5.1324	n	n	0.4577	0.2825	0.2457	0.1868	0.2908	0.2832	0.343
CO_2 (kg)	0.868	n	n	0.064	1.651	0.073	0.063	1.018	0.984	0.356

$Price_{pump}$ = 12€/unit

FIGURE 4 First step of the hybridization process: conversion of corresponding EEIOA data using the price of the product (requires correction for double counting)

the practitioner to force EEIOA inputs to zero for data that are known (or considered) to be complete, including null inputs. Equation (7) is therefore modified as:

$$c_{Mk}^{SSM} = \theta_{Mk} \cdot \lambda_{Mk} \cdot a_{MK}^{io} \cdot h_{Kk} \cdot \pi_k \tag{10}$$

$$c_{Mk}^{SSM} = \theta_{Mk} \cdot c_{Mk}^{binary} \tag{10'}$$

Method	LCA	EEIOA	HLCA no correction	a) Binary	b) SSM	c) BPC	d) STAM
	Pump (unit)	Machinery (€)	Pump (unit)	Pump (unit)	Pump (unit)	Pump (unit)	Pump (unit)
Pump (unit)	0	-	0	0	0	0	0
Stainless steel (kg)	1	-	1	1	1	1	1
Plastics (kg)	0	-	0	0	0	0	0
Machinery (€)	-	0.07	0.84	0.84	0.84	0.84	0
Steel (€)	-	0.03	0.36	0	0	$0.36-1*\Pi_m$	0
Fabricated metal (€)	-	0.07	0.84	0.84	0.84	0.84	0
Plastic (€)	-	0.001	0.012	0.012	0	0.012	0
Diesel (€)	-	0.001	0.012	0.012	0.012	0.012	0.012
Lubricant (€)	-	0.001	0.012	0.012	0.012	0.012	0.012
Other (€)	-	0.4003	4.8036	4.8036	4.8036	4.8036	4.8036
Added value (€)	-	0.4577	5.1324	5.1324	5.1324	5.1324	5.1324
CO_2 (kg)	0.1	0.064	0.868	0.1	0.1	0.768	0.1

FIGURE 5 Different hybrid inventories for different methods to correct for double counting

Where coefficients of $\boldsymbol{\Theta}$ are determined as follows:

$$\theta_{Mk} = \begin{cases} 0 & \text{if any } a^{lca}_{mk} = 0^* \\ 1 & \text{otherwise} \end{cases}, \quad \begin{cases} \forall M, k \\ \forall m \in M \end{cases} \tag{11}$$

If there is any a^{lca}_{mk} known to be zero by the practitioner ($=0^*$), then θ_{Mk} is set to zero. Otherwise the complement is left untouched.

Applied to the production of the pump, if the practitioner is aware that it does not require plastics (m), θ_{Mk} is set to zero with M being the plastic product group and k being the production of the pump, which ultimately results in a null complement for Plastics (c^{SSM}_{Mk}) in the upstream cut-offs (Figure 5b).

4.2.3 | By-product correction

The BPC is also regularly used in HLCAs (Acquaye et al., 2011; Strømman, Solli, & Hertwich, 2006; Williams, 2004). Strømman et al. (2009) coined the name for it: by-product correction. Instead of setting coefficients to zero whenever they are included into both representations, the BPC consists in subtracting the monetary value of the inputs covered by the LCA inventory from the EEIOA complement. Equation (7) is modified subsequently:

$$c^{BPC}_{Mk} = a^{io}_{MK} \cdot h_{Kk} \cdot \pi_k - \sum_{m \in M} \left(a^{lca}_{mk} \cdot \pi_m \right), \{\forall M, k \tag{12}$$

$$c^{BPC}_{Mk} = c^{uncorrected}_{Mk} - \sum_{m \in M} \left(a^{lca}_{mk} \cdot \pi_m \right), \{\forall M, k \tag{12'}$$

where a^{lca}_{mk} corresponds to the LCA input m for the process k and πm corresponds to the price of the LCA input m.

Applied to our example, this method results in a –0.39€/unit coefficient for steel, coming from the uncorrected coefficient (0.36€/unit) from which we retrieved the monetary value of the stainless steel represented by LCA ($\pi_m = 0.75$€/kg), see Figure 5c).

4.2.4 | Tier-wise purchase correction

Strømman et al. (2009) introduced in the same paper the tier-wise purchase correction (TPC) to avoid potential negative values introduced using BPC. Instead of subtracting the value of an LCA flow ($a^{lca}_{mk} \cdot \pi_m$) from the direct input flows of M ($a^{io}_{MK} \cdot h_{Kk} \cdot \pi_k$) in the EEIOA complement, it spreads the retrieval over other indirect inputs of M over the value chain. In order to identify the flows from which to retrieve, structural path analysis (SPA) is used (Defourny & Thorbecke, 1984). The monetary value of the LCA representation is subtracted from the top-ranking paths identified by the

SPA. For the illustrative example, the path CO_2 > Steel > Pump > User is the top-rank path and is visible in the matrix (0.36€/unit). Other paths available would be CO_2 > Steel > Fabricated metal > Pump > User for example, but such higher order paths cannot be visualized in a coefficient matrix. The monetary value of the double counted input (0.75€/unit) is retrieved as much as possible from the top-ranked path which results in 0, the remainder (0.39€/unit) is then retrieved from the next highest-rank path and so on. Representing the effect of the TPC in a matrix is impossible for the example we chose, since some of the changes introduced by the method occur beyond the scope of what is visible with a matrix representation. For more insights into how the TPC is applied to our example refer to Supporting Information S2.

4.3 | New method: Similar technological attributes method

We introduce a streamlined variant of the SSM with the aim of facilitating the hybridization of extensive datasets: the similar technological attributes method (STAM). Like the SSM and the binary method, STAM forces to zero the $\boldsymbol{C}^u$ coefficients from EEIOA product groups (M, K) for which LCA inventory (for the production of products m, k) already records a product flow (a^{lca}_{mk}, with $m \in M$). Just like SSM, it also introduces additional matrices to preserve null inputs that are deemed to not result from truncation but rather from the specificity of each technology in the LCA process. However, contrary to SSM, it does not rely on the analysis of each individual LCA process that is hybridized. Rather, the correction for double counting is streamlined in terms of a set of heuristics applicable to broad *categories* (i.e., collections of product groups sharing similar input structures). For instance, all processes for the production of Machinery and equipment, Office machinery, Electrical machinery (product groups from Exiobase) may be deemed to have similar physical characteristics and be regrouped in the same category (*Machines*), as they all require similar inputs (in different quantities) such as plastic, steel, and electronic components. Then, based on these heuristics, if all inputs from processes that belong to category $\mathcal{M}$ are deemed to be thoroughly covered in all LCA inventories of processes of category $\mathcal{K}$, this is recorded in matrix $\boldsymbol{\Gamma}$ such that EEIOA complements will be forced to zero for all product groups $M \in \mathcal{M}$ in the hybridization of all processes $k \in \mathcal{K}$.

It results in a coefficient $\gamma_{\mathcal{M}\mathcal{K}}$, which can be expressed as follows:

$$\gamma_{\mathcal{M}\mathcal{K}} = \begin{cases} 0 & \text{if } \mathcal{M} \text{ respects heuristics applicable to } \mathcal{K} \\ 1 & \text{otherwise} \end{cases}, \quad \{\forall\, \mathcal{M},\ \mathcal{K} \tag{13}$$

It may then be recorded in $\boldsymbol{\Gamma}$ that, for the hybridization of all processes that belong to *Machines* (e.g., the pump), inputs that belong to the category *Plastics* are assumed to be thoroughly covered in the LCA inventory and require no complement. Based on what could such category-wide judgements be made? We propose three heuristics:

1. Respect of the fundamental balances: As LCA databases get progressively refined, they explicitly strive to respect conservation of mass, carbon, and so forth (Weidema, 2011; Weidema et al., 2013). This increases the confidence that certain categories of null inputs are null to reflect the absence of inputs, rather than as a result of truncation and should therefore not be altered. Thus, if an LCA process is mass balanced, we can reasonably assume that all inputs from categories with the potential to contribute to the mass of the product have been inventoried; and the EEIOA complement should not alter the representation of these flows.

For example, all inputs from the category *Plastics* used in the production of machines (from the category *Machines*) are likely to be embedded in the final product and thereby contribute to their mass. Consequently, all EEIOA complements belonging to this *Plastics* category will be forced to zero in the hybridization of all machines. Conversely, plastic requirements are not embedded in final products of the *Grain* category (e.g., for packaging purposes), and may have been omitted by the LCA practitioner without disrupting mass balance; in that case, inputs from the *Plastics* category would be added as complements to all processes of the *Grain* category.

2. Expert knowledge at database level: Not all inputs that have a mass contribute to the mass of the final product, as multiple usages are dissipative or consumptive. For example, the application of fertilizers in the production of grain is not embedded in the grain (heuristic 1 thus does not apply) and may be truncated even in a mass-balanced LCA process. Nevertheless, through dialogue with database providers, it may be evaluated to what extent they are confident that a certain category of inputs has been appropriately covered: confirming, for example, that all processes from the *Grain* category have thoroughly been inventoried in terms of all inputs from the *Fertilizers* category. The absence of fertilizers may therefore constitute a specificity of the technology (e.g., organic agriculture) rather than a truncation. This second rule follows the same logic as SSM, but it is applied to large categories of products for speed and efficiency. Such understanding may be directly embedded in the $\boldsymbol{\Gamma}$ matrix.

The introduction of these two heuristics refines the previous definition (11) of $\gamma_{\mathcal{M}\mathcal{K}}$ as follows:

$$\gamma_{\mathcal{M}\mathcal{K}} = \begin{cases} 0 & \text{if } \mathcal{M} \text{ involved in the fundamental balance of } \mathcal{K} \\ 0 & \text{if } \mathcal{M} \text{ deemed fully covered in inventories of } \mathcal{K},\ \{\forall\, \mathcal{M},\ \mathcal{K} \\ 1 & \text{otherwise} \end{cases} \tag{14}$$

$\gamma_{\mathcal{MK}}$ being set to 0 if category $\mathcal{M}$ participates to the mass of category $\mathcal{K}$ or if category $\mathcal{M}$ is deemed to have been thoroughly covered in all inventories of category $\mathcal{K}$, 1 otherwise.

3. Equal coverage within categories: As a third heuristic, we may assume that if an input is present in a process-based inventory, inputs with similar functionalities have been investigated as well by the data collector. Indeed, if an input of diesel has been accounted for, it is unlikely that the data collection omitted to account for inputs from the same functional category (i.e., *Liquid Fuels*) such as kerosene or gasoline. Most likely these were left null because the machine runs on diesel and not on any other functionally competing liquid fuel. Another possibility is that the data collector had no idea which of diesel, gasoline or kerosene is used in reality and assigned all energy requirements to diesel. In both cases though, adding kerosene/gasoline inputs from EEIOA would correspond to a double counting incident. Categories whose associated products have similar functionalities ($\mathcal{F}$) are therefore flagged in STAM. Then, the presence of an LCA input belonging to such categories sets other inputs belonging to that category to zero. Mathematically it corresponds to introducing another matrix Φ (different from $\mathbf{\Gamma}$ since both matrices rely on different mechanics and do not have the same dimensions) defined such as follows:

$$\varphi_{Mk} = \begin{cases} 0 & \text{if} \sum_{n \in N} a^{lca}_{nk} \neq 0 \\ 1 & \text{otherwise} \end{cases}, \quad \begin{cases} \forall\, M, N \in \mathcal{F} \mid M \neq N \\ \forall\, k,\ \mathcal{F} \end{cases} \tag{15}$$

where φ_{Mk} is equal to 0 if there is a non-null LCA input *n* belonging to the product group *N* which belongs to $\mathcal{F}$ while *M* also belongs to $\mathcal{F}$. Otherwise φ_{Mk} is equal to 1 and thus leaving the upstream cut-off coefficient unaffected. Both $\mathbf{\Phi}$ and $\mathbf{\Gamma}$ are then introduced in Equation (8), and two concordance matrices (***G***, ***H***) enable the passage between categories, product groups, and products:

$$c^{STAM}_{Mk} = (g_{M\mathcal{M}} \cdot \gamma_{\mathcal{MK}} \cdot g_{K\mathcal{K}} \cdot h_{Kk}) \cdot \varphi_{Mk} \cdot \lambda_{Mk} \cdot a^{io}_{MK} \cdot h_{Kk} \cdot \pi_k \tag{16}$$

$$c^{STAM}_{Mk} = (g_{M\mathcal{M}} \cdot \gamma_{\mathcal{MK}} \cdot g_{K\mathcal{K}} \cdot h_{Kk}) \cdot \varphi_{Mk} \cdot c^{binary}_{Mk} \tag{16'}$$

An example of $\mathbf{\Gamma}$ is given in Supporting Information S2 for a better understanding. STAM constitutes a formalized and refined version of hybridization workflows previously discussed in Majeau-Bettez & Maxime (2015) and Majeau-Bettez et al. (2017). The application of all methods is detailed in Supporting Information S2.

5 | ANALYSIS

5.1 | Assumptions

All the introduced methods can be divided into two different families based on a core assumption on truncations in LCA: the methods assuming that LCA covers at least some inputs completely (Binary, SSM, and STAM) and the methods that assume that all LCA inputs are potentially under-estimated (BPC and TPC) (Figure 6). The binary method assumes that LCA is not truncated on inputs that it explicitly contains in its process-based LCI. Applied to the pump, it means that the stainless steel inputs represent the total requirements of stainless steel of the actual technology, thus it is kept intact. That method requires no additional knowledge of the process to be applied (see Figure 6).

The SSM additionally assumes that an LCA process is not truncated on some additional inputs, specified by the practitioner. As such, the position of SSM in Figure 6 varies depending on the practitioner's knowledge of the process (thick gray arrow). The more the practitioner knows about the process and has first-hand understanding of what is not required by the process, the more null inputs values they will keep untouched. Notice that if the practitioner has no expert knowledge of the process to be hybridized, $\mathbf{\Theta}$ becomes a matrix of ones and SSM is reduced to the binary method. Furthermore, SSM can yield the same results as STAM, but for both to become equal it would require a disaggregation of the categories of STAM into product groups (red dotted lines).

STAM assumes that inputs that are embedded in the mass of the product do not suffer from truncations. If an input would be part of the mass of the product (given the physical attributes of its category) but is not explicitly in the process-based LCI (like the plastic of the fictional pump), that is because that input is null and not because no data are available, therefore it should not be completed with EEIOA data. Unlike the binary method, it requires to design categories and determine which categories participate to the mass of which category to then feed that information to the STAM matrices. In addition, STAM also assumes that if an input of a category whose products share the same functionality is included in the inventory, then other equivalent technologies inputs are not missing from the inventory.

BPC and TPC methods belong to the second family, assuming that all LCA inputs suffer from truncation to some degree and have to be complemented by EEIOA. In addition, they consider that the sum of the values of hybrid requirements of the process (*k*) for a particular input (*m*) and its product group (*M*) must stay equal to the sum of EEIOA's coefficients for that input's product group ($a^{lca}_{mk} \cdot \pi_m + c^{BPC}_{Mk} = a^{io}_{MK} \cdot \pi_k$). The sum of hybrid

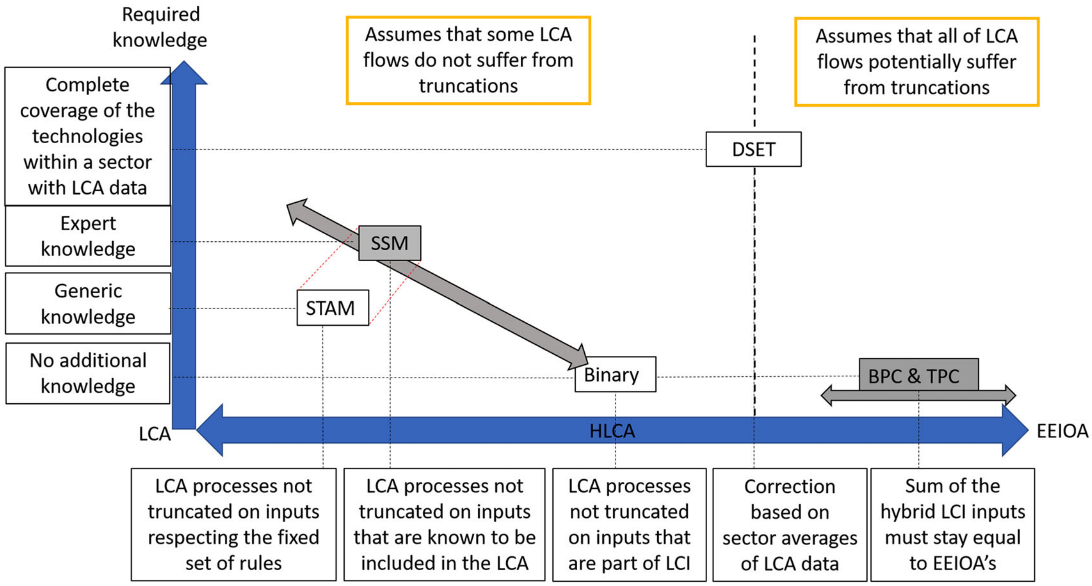


FIGURE 6 Graphical representation to map out relationships between the different methods to correct for double counting

requirements for the steel of our pump, when expressed in monetary units (0.75€/unit + $\mathbf{C}^u$ coefficient from the steel product group) must be equal to EEIOA's inputs for the steel (0.03€/€ of Machinery * 12€/unit) which gives −0.39€/unit for c^{BPC}. These methods do not require additional knowledge, as the prices should already be known by the practitioner. Their position on Figure 6 also varies depending on how much of the system is hybridized, as will be discussed later in the article.

5.2 | Further development: Database sampling estimation of truncations

Methods from the right or left sides of the dotted line (in Figure 6) are based on the two previous extreme assumptions, which could be bridged and refined by a better understanding of the typical coverage of LCA databases for the various categories of inputs in the different product groups. In other words, answering the question: "In average, how much are the inputs of product (*m*) truncated in LCA processes that belong to product group (*K*)?" could serve as an empirical foundation to build a middle ground between the two previous extreme assumptions. That is what the database sampling estimation of truncations (DSET) would strive to achieve and why it is situated *on* the dotted line in Figure 6. Mathematically, it would correspond to (1) performing a weighted average of the LCA processes that belong to a given product group and (2) subtracting the monetary value of these average input flows from the EEIOA representation of this product group, the remainder providing an estimate of the typical truncation level in LCA databases for that product group. However, the validity of this estimate depends on the complete coverage of the technologies of the product groups within the LCA database. In other words, it rests on the assumption that the LCA database contains a thorough sample of all technologies for each product group, and that representative production volumes are available, such that, in theory, the two representations should be equal if not for truncation issues. However, for now, even for the ecoinvent database (Wernet et al., 2016), one of the most developed LCA database, the necessary quality data and coverage is not yet there, even for very detailed product groups (e.g., the electricity, steel, and cement product groups). Yet, it remains a promising approach as LCA database continue to develop. An attempt to apply the DSET to the electricity processes of ecoinvent v3.3 is available in the Supporting Information S2.

5.3 | Limitations

Each of the previously presented methods suffers from limitations. The first limitation concerns the incorrect introduction of inputs as EEIOA complements. The binary method relies on the explicit coverage of inputs in the inventory. The problem is that an inventory does not typically contain explicit null inputs. In the example we implemented, it is given that the pump does not require plastics, yet hybridization with the binary method includes plastics in its hybrid inventory (Figure 5a). The BPC and TPC introduce plastic in the hybrid inventory of the pump too. However, we established that these two methods consider that all inputs of LCA suffer from truncation. It therefore does not correspond to a limitation but to the assumption itself for these two methods. As for SSM and STAM, this limitation is what prompted the implementation of the theta and STAM matrices, which both deal with the issue.

The second limitation of some of the methods is directly linked to how inventories are constructed. In LCA, there is no standard resolution at which to illustrate the product system, and even if the whole supply chain is considered, the different processes can be aggregated depending on the resolution (as illustrated in Figure 2), while EEIOA enforces a strict product-group classification. When looking at the hybrid inventory obtained from the binary method (Figure 5a), the coefficient coming from the fabricated metal product group (corresponding to the prefabricated steel parts of the pump) is left untouched. As a result, part of the steel has been corrected (the coefficient from the steel product group has been set to zero) but part of the steel is still double counted (because the fabricated metal complement is left untouched). The SSM can deal with this issue but it requires the LCA practitioner to be aware of the potential occurrence of this limitation and appropriately modify the theta matrix. In the example we expose, the LCA practitioner is considered not being aware of the issue, which results in the noncorrection of the prefabricated steel parts too (Figure 5b). The Γ matrix of STAM on the other hand, allows to efficiently correct double counting emerging from the low-resolution of product systems. Indeed, steel and fabricated metal belong to a category (*Metals)* which is part of the mass of the pump, thus resulting in a coefficient forced to zero for both product groups (Figure 5d). All the steel is therefore corrected even with minimal understanding. BPC and TPC also deal appropriately with this issue as they subtract the total monetary value of the steel as viewed by LCA (i.e., steel + parts of steel), regardless of the level of aggregation of the inventory.

SSM possesses a practical limitation that other methods do not suffer from: efficiency. To expose this issue, one needs to think about massive hybridization, like the hybridization of ecoinvent v3.3 (about 14,000 processes). It would then require creating a theta matrix for all these processes. More precisely, it requires filling a 200 × 14,000 matrix manually (using the 200 product groups from Exiobase) and take into account the specific characteristics of each flow, like the problem between steel and steel parts described previously. This issue was the main motivation behind the definition of the STAM.

When applying the BPC, the monetary value of the LCA-covered double counted inputs is subtracted from a single EEIOA complement. If the LCA value of the input is greater than the value of the complement, it will introduce a negative value in the hybrid inventory, like is shown (in Figure 5c). This negative value itself does not create any inconsistency for the result of the analysis. However, it has implications when interpreting the results. That is the reason why in the same article, Strømman and colleagues introduced the TPC which was developed to deal with this problem by spreading the retrieval, thus not introducing negative values.

As stated previously in its description, the TPC relies on SPA and subtracts the monetary value of LCA-covered double counted inputs from the top-ranked paths. However, these top-ranked paths can correspond to inputs not in relation with the double counted input. For instance, among the top-ranked paths for the studied pump, there could have been CO_2 > Steel > Building > Pump > User which corresponds to the steel required by the infrastructure of the location where the pump is produced. In that case, the monetary value of the steel used to manufacture the pump would have been subtracted from another steel: the one used to build the infrastructure. This issue has been highlighted by both Strømman (2009) and Lenzen (2009).

On a final note, uncertainties are a big problem for all these methods, as well as for hybrid LCA itself. Sensitivity analyses, Monte Carlo analyses, and pedigree matrices should ultimately be applied to several aspects of hybrid LCA and of these methods, such as the concordances between products and product groups, the expert knowledge required to apply SSM, the more generic knowledge required by STAM, EEIOA data, and price data.

5.4 | Financial balance in HLCA

Among the introduced methods, three of them force coefficients to zero (binary, SSM, and STAM). By doing so, the financial balance of EEIOA is broken, because the sum of a column ($\boldsymbol{A}^{lca}$ inputs, $\boldsymbol{C}^{u}$ inputs and added value) expressed in monetary terms does not necessarily amount to the price of the product anymore. The financial balance has to be re-established, being a requirement of EEIOA and an essential quality check for the validity of an economic process. Yet, when applying these hybridization methods to product flows, practitioners never address this issue. Implicitly it means that the rescaling occurs on the added value (nonproduct flows) alone, and since added value has no environmental impacts, nothing changes on the HLCA emissions. However, Strømman and Solli (2008) proposed to use the price model of Leontief to rescale the added value *and* the $\boldsymbol{C}^{u}$ coefficients instead of only rescaling the added value. Applying this adjustment has an impact on HLCA (Figure 7) either decreasing or increasing the EEIOA complements. The price model adjustment considers that an increase in the technology requirements compared to the average technology due to the introduction of specific LCA data in the hybrid inventory should be balanced by a decrease of the EEIOA complements and vice versa. Applied to the binary method for the pump, the latter requires 1 kg of stainless steel (0.75€/unit) which is more than is typically required by an average machine (0.36€/unit), thus, applying the price model adjustment means that since more steel is required (from the LCA inventory) and that the price of the pump does not change, fewer materials, services, and so forth must be used and less profit made. On the other hand, rescaling only onto the added value means that, even if more steel is required, the same amount of materials, services, and so forth are used and even less profit is made. The influence of the application of the price model on emissions is shown in the Supporting Information S2.

5.5 | Hybridization and environmental matrix

There have been recent developments on the number of elementary flows considered in EEIOA (Stadler et al., 2018; Suh, 2009; Yang, Ingwersen, Hawkins, Srocka, & Meyer, 2017) leading to a point where some EEIOA tables include more elementary flows than LCA. However, to the best of the authors' knowledge, no hybrid LCA has ever hybridized elementary flows and environmental extensions, focusing only on the hybridization of economic flows. Yet, the elementary flows are bound to the technological description and modifying the technological description of a process

Method	Binary	Binary + Price model	SSM	SSM + Price model	STAM	STAM + Price model
	Pump (unit)	Pump (unit)	Pump (unit)	Pump (unit)	Pump (unit)	Pump (unit)
Pump (unit)	0	0	0	0	0	0
Stainless steel (kg)	1	1	1	1	1	1
Plastics (kg)	0	0	0	0	0	0
Machinery (€)	0.84	0.810	0.84	0.811	0	0
Steel (€)	0	0	0	0	0	0
Fabricated metal (€)	0.84	0.810	0.84	0.811	0	0
Plastic (€)	0.012	0.011	0	0	0	0
Diesel (€)	0.012	0.011	0.012	0.011	0.012	0.013
Lubricant (€)	0.012	0.011	0.012	0.011	0.012	0.013
Other (€)	4.8036	4.6447	4.8036	4.6594	4.8036	5.4393
Added value (€)	4.7304	4.9502	4.7424	4.9553	6.4224	5.7971
CO_2 (kg)	0.1	0.1	0.1	0.1	0.1	0.1

FIGURE 7 Rescaling either of value added (in blue) or of the whole hybridized EEIOA complement (price model adjustment) to ensure the respect of financial balance in the hybrid inventory (in red)

through hybridization should have consequences on its elementary flows, which should in other words, be hybridized themselves. For instance, if the hybridization of a machine introduces (additional) diesel input flows, this higher consumption of fossil fuels should be mirrored by an increase in direct emissions of the process, notably of particulate matter. Through consistent hybridization, these additional emissions may be estimated based on the emission of particulate matter in EEIOA environmental extensions ($\boldsymbol{B}_{io}$). Conversely, should the environmental extensions not be hybridized, there would be additional consumption of diesel *without* additional emissions of particulate matter, which essentially distorts the production function.

When hybridizing the environmental extensions, the same double-counting correction method used for the technology matrix should be used. The hybridization of elementary flows for the pump results in null complements of CO_2 for the binary method, SSM, and STAM, because LCA already covered CO_2. However, for BPC and TPC the EEIOA value of CO_2 emitted is kept, resulting in a 0.768 kgCO_2/unit total (Figure 5c).

5.6 | BPC/TPC can cancel hybridization efforts

In most current hybrid LCAs, only some key processes of the system (foreground) are hybridized while the rest of the system is not (Strømman et al., 2009). The BPC and TPC focus on setting the sum of hybrid inputs to equal the sum of EEIOA's inputs. The total value for the inputs of the hybrid LCA will therefore be identical to that of the EEIOA and the same goes for the elementary flows. However, HLCA and EEIOA will still yield different results because the hybrid inventory uses specific LCA inputs instead of the average inputs of EEIOA, meaning that it retains specificity through nonhybridized processes. However, once these LCA processes are all hybridized as well and forced to respect EEIOA proportions, this specificity will be lost. In other words, if BPC or TPC is applied to a complete process-LCA database and its environmental extensions, calculations relying on the resulting system description will necessarily yield identical results as if they had been performed with the original EEIOA (as demonstrated in the Supporting Information S2). That is why in Figure 6, the BPC/TPC position can change depending on how much of the system is hybridized, reaching all the way to the extreme right-hand of the scale, that is, a system equivalent to pure EEIOA.

6 | CONCLUSION

When choosing between these methods, BPC and TPC should not be selected if the hybridization scope is a full system (like a whole database), but BPC and TPC can be used on a limited number of processes, if their volumes of the flows are uncertain. As for the other methods, it corresponds to a trade-off. The choice between binary, SSM, and STAM should be guided by the level of knowledge of the hybridization practitioner about each process as well as the scope of the hybridization. To perform a hybridization without having to obtain additional information, the binary method should be used. If a high-quality hybridization is wanted, SSM should be applied, keeping in mind that it requires extensive time and resources to feed information to the theta matrix. Finally, for a hybridization which requires minimal additional knowledge and yet still delivers more refined results than the binary method, STAM should be applied. It is also important to keep in mind that the binary method, due to its limitations, does not correct all the double counting incidents while STAM corrects double counting incidents more comprehensively. However, since more LCA inputs are left untouched, an HLCA using STAM will be more prone to truncations than an HLCA using the binary method. In other words, STAM takes a conservative approach, and there is a higher likelihood that STAM corrects too much for double counting, whereas there is a higher chance that the binary method does not correct enough for double counting. Since the SSM is a customized approach in which the practitioner has explicit control over which LCA data he keeps or not, with the proper knowledge, the SSM allows to not over- or undercorrect.

This article provided insights about the different ways to deal with double counting incidents in HLCA. We presented four already existing methods (Binary, SSM, BPC, and TPC), introduced a new streamlined variant (STAM) as well as a conceptually distinct approach (DSET) that should gain in relevance as the databases cover more and more existing technologies. The article explained how the methods were correcting for double counting with a common notation, as well as their assumptions and limitations through an illustrative example. We also introduced the necessity to hybridize (and thus correct for double counting) the environmental extensions with the same correction method that was used for the technology matrix. Currently the hybrid community only focuses on the hybridization of the technology matrix, leaving the environmental matrix untouched which can trigger inconsistencies (no increase in emissions of particulate matter even though more diesel is consumed).

A recurring aspect of the correction for double counting is the question of null inputs in inventory. Is an input set to zero because it is indeed not used in the technology or is it because no data is available? In the first case, the corresponding complement should be put to zero while it should be left in C^u for the second (for binary-like methods). However, to the best of our knowledge this information is not registered in inventories leaving hybrid practitioners guessing with heuristics, if they are not the ones who gathered the data initially. There is therefore a need notably for database providers to distinguish which data are known to be zero and which data are unavailable.

All methods presented throughout this article can be considered to carry out the correction of double counting (and by extension HLCA itself) in an ad hoc way. The challenge in HLCA is determining whether the data provided by LCA is truncated or not, and eventually by how much. This could be achieved with a deeper understanding of the uncertainties in LCA, meaning that HLCA could ultimately be treated as a statistical problem.

Finally, we would like to encourage hybrid practitioners to explicitly declare which methods and assumptions were employed in the correction for double counting, whether or not they hybridized the environmental matrix, and how they rebalanced the system (price model or not). HLCA is a complex methodology that requires all of the hybrid community to thoroughly detail studies so that they can potentially be reused, reproduced or adapted to a different context. A more comprehensive description of HLCA studies will also help practitioners new to hybridization to have a better grasp on the strengths and weaknesses of hybridization leading to a wider adoption within the field, for more complete and detailed sustainability analyses.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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