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Titre: Title: Choice of allocations and constructs for attributional or consequential life cycle assessment and input-output analysis

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Date: 2018

Type: Article de revue / Article

Référence: Citation: Majeau-Bettez, G., Dandres, T., Pauliuk, S., Wood, R., Hertwich, E., Samson, R., & Strømman, A. H. (2018). Choice of allocations and constructs for attributional or consequential life cycle assessment and input-output analysis. Journal of Industrial Ecology, 22(4), 656-670. https://doi.org/10.1111/jiec.12604

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Version: Version finale avant publication / Accepted version
Révisé par les pairs / Refereed

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Document publié chez l'éditeur officiel
Document issued by the official publisher

Titre de la revue: Journal Title: Journal of Industrial Ecology (vol. 22, no. 4)

Maison d'édition: Publisher: Wiley & Yale University

URL officiel: Official URL: https://doi.org/10.1111/jiec.12604

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Choice of Allocations and Constructs for Attributional or Consequential Life Cycle Assessment and Input–Output Analysis

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January 29, 2017

Abstract

The divide between attributional and consequential research perspectives partly overlaps with the long-standing methodological discussions in the lifecycle assessment (LCA) and input–output analysis (IO) research communities on the choice of techniques and models for dealing with situations of coproduction.

The recent harmonization of LCA allocations and IO constructs revealed a more diverse set of coproduction models than had previously been understood. This increased flexibility and transparency in inventory modeling warrants a re-evaluation of the treatment of coproduction in analyses with attributional and consequential perspectives.

In the present article, the main types of coproductions situations and of coproduction models are reviewed, along with key desirable characteristics of attributional and consequential studies. A concordance analysis leads to clear recommendations, which call for important refinements to current guidelines for both LCA/IO practitioners and database developers. We notably challenge the simple association between, on the one hand, attributional LCA and partition allocation, and on the one hand, consequential LCA and substitution modeling.

1 Introduction

1.1 Aim of study

The research on sustainable development takes different perspectives: historic, descriptive, imputational, predictive, explorative, or normative (Zamagni et al., 2012; Fischer-Kowalski and Hüttler, 1999; Ehrenfeld, 2004; Ekvall et al., 2005; Börjeson et al., 2006; Pauliuk and Hertwich, 2016). Addressing this plurality of perspectives constitutes an ongoing challenge for the development of industrial ecology models, notably lifecycle assessments (LCAs), environmentally extended input–output analyses (EEIOs), and material flow analyses (MFAs).

During the early stages of LCA development, it was postulated that a lifecycle description could be used to answer questions of *attribution* of impacts to specific human activities, and also questions pertaining to the *consequences* of a potential change in these activities (Heijungs,

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1997; Tillman, 2000). This plurality of question types spurred the development of recommendations to better align data selection and modeling choices with different research objectives (Heijungs, 1997; Tillman, 2000; Guinée, 2002; Weidema, 2003; Ekvall et al., 2005; Sandén and Karlström, 2007; Schrijvers et al., 2016). This article aims to further these efforts and enhance the internal consistency of environmental systems analysis, focusing on the issue of coproduction modeling in LCA and EEIO.

The modeling of multifunctionality —LCA allocations[1] and EEIO constructs— is one of the most debated methodological choices within industrial ecology (notably, Kop Jansen and ten Raa, 1990; Konijn and Steenge, 1995; Heijungs, 1997; Londero, 1999; Weidema, 2000; Atherton, 2006; Bohlin and Widell, 2006; Heijungs and Guinée, 2007; Cherubini et al., 2011; Ardente and Cellura, 2012; ten Raa and Rueda-Cantuche, 2013), and it is a central divide between the attributional and the consequential modeling approaches (Finnveden et al., 2009; Brander and Wylie, 2011; Zamagni et al., 2012). Recent efforts to harmonize LCA allocations and EEIO constructs (Suh et al., 2010; Majeau-Bettez et al., 2014, 2016) have broadened the spectrum of available coproduction models, which warrants a re-evaluation of their concordance with various research objectives. This article then asks, *"What LCA allocations and EEIO constructs, applied to what type of coproduction, are most consistent with attributional or consequential research questions?"*. This issue is of crucial importance to ensure clarity and credibility, not only for individual studies but also for the ongoing development of LCA databases with attributional and consequential versions (Wernet et al., 2016; Steubing et al., 2016).

1.2 Background and scientific context

1.2.1 The problem of coproduction

To calculate the environmental or social impacts directly and indirectly associated with a set of production or consumption flows, both LCA and EEIO require that the industrial system be fully described in terms of monofunctional unit processes, also known as technological "recipes," single-output processes, or Leontief production functions (Leontief, 1970; Guinée, 2002; Miller and Blair, 1984; Koesler and Schymura, 2015). Each technological recipe is assumed to be associated with a single, distinct, homogeneous product (Leontief, 1936; Konijn and Steenge, 1995; Viet, 1994; Bidard and Erreygers, 1998; Weisz and Duchin, 2006; Majeau-Bettez et al., 2016). Consequently, activities that supply more than one product, —such as a grain farmer coproducing wheat and straw, or the electronics sector coproducing laptops and cellphones— prove challenging for lifecycle calculations.

If a coproduction situation artificially arises due to the level of aggregation, the preferred solution is clearly to disaggregate the multifunctional description with additional data (ISO 2006). For example, further inquiry may reveal that laptops and cellphones are in fact produced in different facilities, each with their own distinct value chains, and the multi-output electronics sector could then be sub-divided into multiple single-output sectors. Alternatively, if the coproducts of an activity are always consumed together and in the same ratio as their production ratio, it is possible to avoid modeling assumptions by defining the "bundle" of these coproducts as the homogeneous output of the activity in question. This strategy is reflected by the pseudo-inverse technique in the case of intermediate consumption (Heijungs and Frischknecht, 1998), and by the classical definition of system expansion in the case of final consumption (Guinée, 2002; Wardenaar et al., 2012; Heijungs, 2014).

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[1] As pointed out by Heijungs and Guinée (2007), the term "allocation" is either used to indicate the partitioning (splitting) of requirements across multiple functions or, in a broader sense, to designate any modeling solution to the "allocation problem" (i.e., coproduction/multifunctionality). Throughout this article, we use this term's broader meaning, which we further define in section 3.

In any other coproduction situation, however, linear LCA and EEIO models require the definition of monofunctional processes from initially multifunctional descriptions, embedding assumptions in the lifecycle calculation (United Nations, 1999; Guinée, 2002; European Commission, 2008). The merits and shortcomings of these different coproduction models have been extensively discussed. The LCA community has contrasted the two main modeling approaches, partition and substitution, in terms of their epistemological foundations, levels of physical realism, compliance with ISO standards, subjectivity, and relation to the definition of system expansion (Weidema, 2000; Heijungs and Guinée, 2007; Weidema and Schmidt, 2010; Cherubini et al., 2011; Ardente and Cellura, 2012; Wardenaar et al., 2012; Jung et al., 2013, among others). In the input–output analysis (IO) community, different constructs have been lauded or criticized based on their level of transparency (Suh et al., 2010), their introduction of negative coefficients (Almon, 2000; ten Raa and Rueda-Cantuche, 2013), their economic credibility (Viet, 1994; United Nations, 1999), their capacity to respect fundamental balances (Kop Jansen and ten Raa, 1990; Majeau-Bettez et al., 2016), and their robustness to changes in production volumes or prices (Kop Jansen and ten Raa, 1990).

1.2.2 The attributional and consequential questions

In his seminal thesis, Heijungs (1997) laid the epistemological foundations of the attributional problem, which he described as "the question of which environmental problems are to be attributed [or assigned] to which economic activities." Heijungs (1997) argues for a fundamental distinction between the attribution question and "the question of [estimating the environmental] effects of changes" in economic activities, pointing to at least "two major types" of LCA. The definition of such a change-oriented, consequential LCA has since been developed by a vast body of literature (notably Weidema, 2003; Ekvall and Weidema, 2004; Ekvall and Andrae, 2006; Lesage et al., 2006; Weidema et al., 1999; Dandres et al., 2011; Lan et al., 2012). As for the attribution problem in LCA, its methodology has also been further refined (e.g., Suh et al., 2004; Frischknecht and Stucki, 2010) and expanded for *prospective* attributional analyses (Spielmann et al., 2005; Sandén and Karlström, 2007; Gibon et al., 2015).

An increasingly clear distinction is thus made between the LCA and EEIO model families that aim to answer questions of attribution and those that aim to estimate the consequences of a perturbation. This distinction is reflected in the scientific literature (Finnveden et al., 2009; Guinée et al., 2010; Zamagni et al., 2012; Lan et al., 2012), in practitioner guidelines (European Commission, 2010; UNEP and SETAC, 2011), and in core databases like Ecoinvent (Wernet et al., 2016; Steubing et al., 2016).

1.2.3 Treatment of coproduction in attributional and consequential analyses

The LCA literature clearly associates partition-based coproduction modeling with attributional analyses, and substitution-based modeling with consequential analyses (as reviewed by Zamagni et al., 2012; Pelletier et al., 2015; Schrijvers et al., 2016).

With the formal harmonization of LCA allocations and EEIO constructs (Suh et al., 2010; Majeau-Bettez et al., 2014, 2016), it is increasingly evident that the partition-versus-substitution dichotomy prevalent in the literature constitutes an over-simplification. Practitioners have access to (and use) a broader range of coproduction models. This calls for a further refinement of the analysis of these models' concordance with attributional and consequential questions.

1.3 Structure of study and limits to scope

We first review different types of coproduction situations described in the literature (section 2), before briefly presenting the four allocations and construct families identified by Majeau-Bettez et al. (2014) (section 3). We then review the formulations and definitions of the attributional and consequential research questions in the literature, and we compile a list of modeling characteristics desirable for a greater concordance with these research questions (section 4). Combining the insights from these three sections, we are able to draw clear conclusions as to when and if each allocation or construct is coherent with attributional or consequential objectives (sections 5 and 6).

This article solely focuses on the consistency of allocation and construct choices with attributional and consequential research objectives. Many crucial data collection and modeling aspects of attributional and consequential studies are addressed only to the extent that they influence, or are influenced by, coproduction modeling. Providing comprehensive guidance for internally consistent attributional lifecycle assessments (ALCAs) or consequential lifecycle assessments (CLCAs) is beyond the scope of this analysis. Debating the usefulness of these research questions is also beyond our scope, as is the analysis of their alignment with different ethical stances or research paradigms (see, e.g., Hertwich et al., 2000; Ekvall et al., 2005; Pelletier et al., 2015).

The distinction between CLCA and ALCA gets blurred in practice, notably through the use of common databases, a general lack of appropriate data, legitimate simplifying assumptions, or internal inconsistencies (Zamagni et al., 2012). We agree with the assertion by Suh and Yang (2014) that such practical considerations must be taken into account when assessing the strengths and weaknesses of the different approaches. However, even if we observe a near continuum of *research practices* between ALCAs and CLCAs, we do not observe such a continuum among clearly formulated *research questions*: either a study strives to assess the impacts that can be attributed to a system[2], or it strives to estimate the impacts of changing this system, or both (separately), but not a “mix” of the two questions. Therefore, and since we focus on methodological consistency, we make a clear distinction between attributional and consequential research questions throughout this work.

The multifunctionality in waste treatment processes, which typically coproduces recycled materials and waste-treatment services, is not fundamentally different from coproduction of goods and services in other industries (see Nakamura and Kondo, 2002; Schrijvers et al., 2016), and consequently our framework is also applicable to these situations.

2 Types of coproduction

Coproduction is defined as the supply of multiple distinct products by a single activity or industry (ISO 2006, Heijungs and Suh 2002).[3] What constitutes a “single activity” and a “distinct product,” however, is partly a question of classification and level of resolution. At one level of resolution, an economic sector may appear to supply a single product, such as steel, whereas at a higher level of resolution, this same sector could be portrayed as coproducing hundreds of different alloys.

Among the coproducts of an industry, a product is typically selected as being the “main,” “primary,” “principal,” “characteristic,” “determining,” or “reference” product (e.g., Viet, 1994; Londero, 1999; United Nations, 1999; Guinée, 2002; European Commission, 2008; Duchin, 2009; Weidema, 2000; Weidema et al., 2009; European Commission, 2010; UNEP and SETAC, 2011). Selecting the main source of revenues as the primary product constitutes a common

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[2] As is widely recognized, this system may be in the past, present or future (Sandén and Karlström, 2007; Finnveden et al., 2009).

[3] Such functional supplies need not necessarily constitute physical outputs, but may equally constitute physical (functional) inputs (Heijungs and Suh, 2002; Weidema, 2014), as is the case for the supply of waste treatment services (different conventions reviewed by Majeau-Bettez et al., 2016).

heuristic (cf. Londero, 1999; Weidema et al., 1999). Any coproduction that is not primary is considered secondary.[4]

Coproduction flows are also classified based on the strength of their technological connections, but LCA and EEIO naming conventions are partly conflicting for this classification (table 1). A coproduction in which coproducts are produced simultaneously and are "causally coupled" are referred to as a *joint production* in the LCA literature (Heijungs and Suh, 2002; Guinée et al., 2004). The stoichiometric production of chlorine gas and caustic soda constitutes a classic example of this. Any secondary product of such a technologically linked coproduction is termed a *byproduct*, especially in the IO literature (United Nations, 1999; European Commission, 2008). Conversely, a coproduction in which "each product is produced by an entirely different technique of production or technology, and [in which] the common administrative costs [. . .] are non-existent or negligible" is called a *combined production* in the LCA community, and the secondary products of such a coproduction are named *subsidiary products* in the IO literature (e.g., Viet, 1994; Konijn and Steenge, 1995; Heijungs, 1997; European Commission, 2008, 2010; United Nations et al., 2009). An alpaca farm also offering on-site tourist accommodation services is an example of combined production with a subsidiary product.

It is widely recognized that there are actually few cases of "pure" (fully independent) subsidiary coproducts or "pure" (fully dependent) byproducts, as the majority of coproductions display an intermediate level of technological coupling, with "some joint costs and some costs that can be attributed to the distinctive outputs" (European Commission, 2008; Suh et al., 2010). The coproduction of milk and meat exemplifies such a situation: the two coproducts are "loosely linked technologically" and "share a significant common cost" —i.e. reproducing and maintaining a herd— but can be produced in various ratios (Viet, 1994; United Nations, 1999). Unfortunately, the term used to describe such intermediate levels of technological linkage in the IO community is "joint production" (Viet, 1994; United Nations, 1999), in direct contradiction with the aforementioned use of the term in LCA.[5] *To avoid confusion, we refer to a coproduction with an intermediate level of technological linkage as a "partial-joint production," in contrast to a "full-joint production."*

Secondary coproducts are also classified based on whether they are produced exclusively as secondary products (exclusive secondary product) or whether there exists at least one industry primarily dedicated to its production (ordinary secondary product) (United Nations, 1999).[6] For example, straw is an exclusive secondary product since it is the primary product of no industry and is always supplied as a secondary product of grain production.

3 Types of allocations and constructs

In this article, an *allocation* refers to a modeling procedure that, without requiring a detailed understanding of the inner mechanism of a coproducing activity, ascribes requirements specifically to the supply of a single product, even though this product is coproduced with others. Whereas LCA allocations are typically defined as resolving individual coproductions, *constructs*

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[4] Most of the literature on allocations and constructs clearly assumes the presence of a single primary/determining product per industry, although the possibility of multiple primary products within a single industry is explicitly considered (Weidema et al., 1999), especially for situations where the choice of a primary production is determined based on a predefined classification scheme (European Commission, 2008, pp. 18 and 43).

[5] It also partly contradicts the use of the term in SNA2008 and Eurostat (United Nations et al., 2009; European Commission, 2008). These use the term "joint product" to designate a somewhat vague intermediate level in a product hierarchy, in addition to primary and secondary products: a type of production which is technologically linked to another product but "cannot be said to be secondary," such as beef and hides.

[6] Again, this can be classification or aggregation dependent (United Nations 1999, p. 95, Majeau-Bettez et al. 2016).

Table 1: Terms typically used in the LCA or EEIO communities and in this article [columns] to designate coproductions with different levels of technological coupling [rows]. Terms in normal font refer to the whole coproduction, whereas terms in italic designate specifically the secondary product or the secondary production. Text in bold highlights a potential conflict regarding the meaning of "joint production" and its proposed resolution (right column).

Technological coupling	LCA term*	EEIO term**	In this article
Complete	**joint** production	*byproduct[ion]*	**full-**joint production *byproduct[ion]*
Partial		***joint*** *product*	**partial-**joint production
None	combined production	*subsidiary product[ion]*	combined production, *subsidiary product[ion]*

*: Heijungs and Suh 2002; Guinée et al. 2004; Heijungs 1997; European Commission 2010
**: Konijn and Steenge 1995; United Nations 1999; European Commission 2008

in IO are traditionally presented as models applicable to the entire inventory of the economy of a region. Constructs generate symmetric product system representations, square technology coefficient matrices, from asymmetric supply and use tables (SUTs) inventories.

All product-by-product[7] constructs can be expressed as a repeated allocation applied in turn to all coproductions of a system, typically followed by an aggregation step in order to yield a single, global production recipe for each product (Majeau-Bettez et al., 2014). Most of this article's analysis of constructs is therefore articulated in terms of their underlying allocations. Unless otherwise specified, our analysis of each allocation also applies to its associated constructs.

3.1 Allocation models

The different allocation models are best reviewed with an example. In fig. 1-I, a fictional grain farming activity requires inputs of 3 units of j and and 4 units of k to coproduce 1 kg of wheat and 2 kg of straw. Modeling can be avoided by classical system expansion in cases where these two products are purchased together in this same ratio; the two coproducts are then jointly assessed, and there is no need to describe the production of one separately from that of the other (fig. 1-II).

With partition allocation (PA), requirements are split proportionately to some common property of the straw and wheat outputs (e.g., mass, energy content, or value). This split is thus calculated using a partitioning coefficient ϕ with a value between zero and one (fig. 1-III). In the special case where the partitioning coefficients equal 1 for the primary product and 0 for any secondary product, this partition allocation (PA) is equivalent to the "surplus method" in the LCA literature (Heijungs and Suh, 2002).

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[7] Contrary to constructs that follow a product-based classification, industry-by-industry constructs lead to IO representations of the economy based on interdependencies between industries. Industry-by-industry constructs are beyond the scope of this analysis because their assumption of fixed sales structure is too far removed from the Leontief assumption of fixed input structures employed in LCA modeling (see Rueda-Cantuche and ten Raa, 2009; Oosterhaven, 1996).

Alternatively, a practitioner may split a coproduction by assuming a stand-alone production technology for secondary coproducts, leaving the remainder of the requirements to the primary product. With alternate-activity allocation (AAA), the technology of an alternate activity (e.g. hay farming, with 1 j and 1 k per kg hay) may be assumed for straw coproduction (1 j and 1 k per kg straw), leaving the remainder of the requirements to wheat production (fig. 1-IV). This modeling can be considered a form of "proxy-based disaggregation."

With product-substitution allocation (PSA), the coproduction is resolved by assuming that secondary coproducts displace some other primary production. For example, if 1 kg of straw can substitute ξ kg of firewood in district heating (assuming they offer the same functionality as fuels), grain farming may be modeled as both supplying wheat and proportionately reducing the production of firewood (inputs of -2ξ kg of firewood in fig. 1-VI). Quantifying the extent to which two products are functionally equivalent and intersubstitutable is a difficult task that must typically take into account multiple properties (Vadenbo et al., 2016). In fact, when two products are so similar that they can be considered perfectly intersubstitutable in terms of all their properties and for all their uses, they can typically be considered as practically identical and classified under the same product category, competing in the same homogeneous market.

Both PSA and AAA have been referred to in the literature under the umbrella term "system expansion." Many models can be considered to "expand the system," but as each model carries additional implications, we find it best to refer to them by specific names rather than the general philosophy that underpins them (in agreement with Wardenaar et al., 2012; Heijungs, 2014).

With lump-sum allocation (LSA), coproducts are simply assumed to be indistinguishable from their primary product. Grain farming would then simply be modeled as producing 3 kg of wheat and no straw (fig. 1-V).

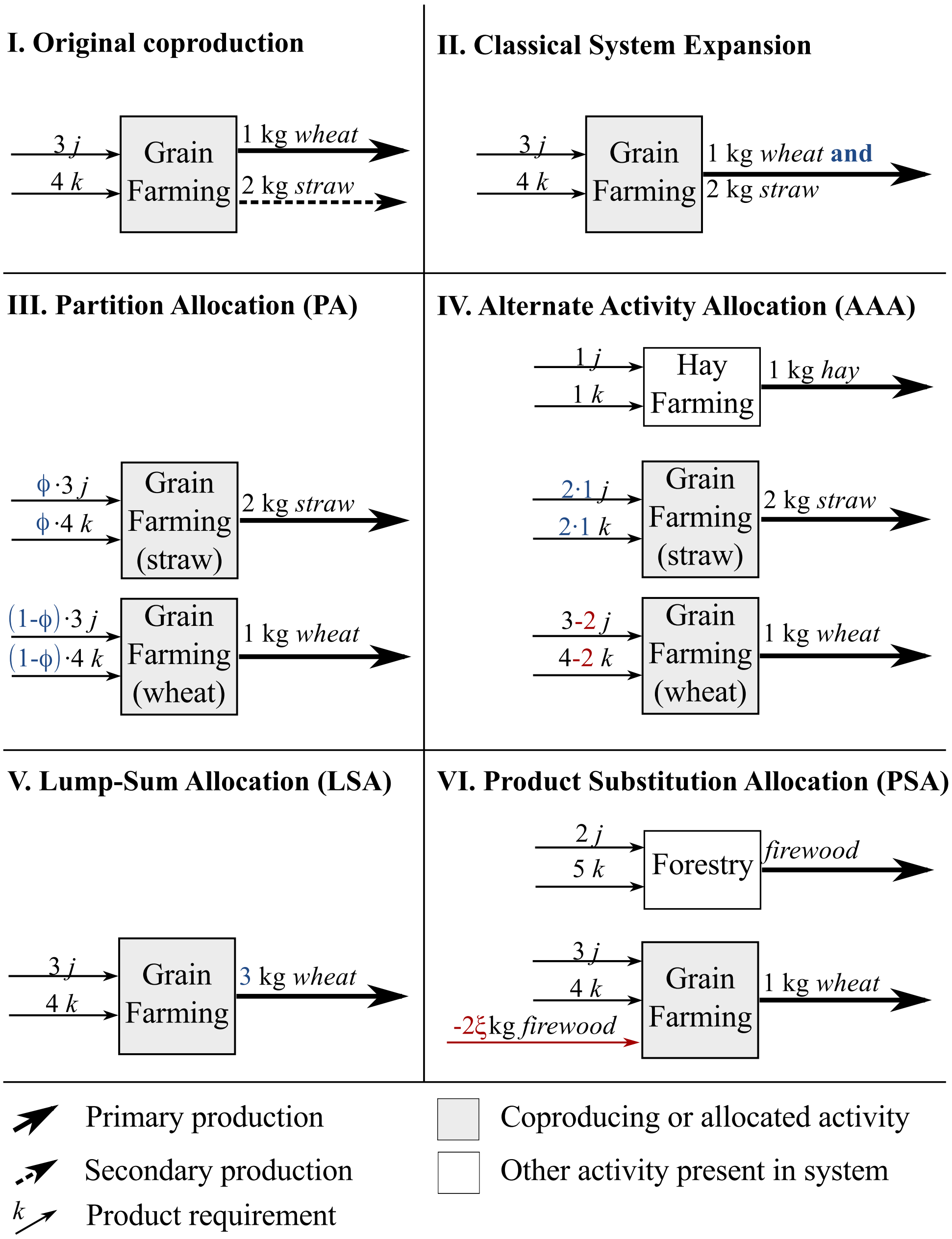

Figure 1: Illustrative example of coproduction (I), classical system expansion (II), and four types of allocation techniques (III–VI). The alternate-activity allocation here assumes a same technology per mass of hay and mass of straw, whereas the product-substitution allocation assumes that each kg of straw can replace ξ kg of firewood.

3.2 Construct models

A partition construct (PC) refers to any construct that is based on PA. Among PCs, the European-system construct (ESC) is based on a specific PA model that ascribes 100% of requirements to the primary product (surplus method). Similarly, the industry-technology construct (ITC) is obtained with a PA that splits requirements proportionately to the property in which the output of each industry is recorded, such as economic PA for an inventory recorded in monetary units, or mass-based PA for mass-based inventory (Majeau-Bettez et al., 2014)

We refer to constructs based on AAA as alternate-activity constructs (AACs). The commodity-technology construct (CTC) is a special case of an AAC in which [i] the system is represented (aggregated) such that there is exactly one primary producer for each product and [ii] all AAA assumptions are based on primary productions of *identical* products, not of products that fall under different categories.

Similarly, a product-substitution construct (PSC) designates any constructs based on PSA. In the special case where every coproduction perfectly displaces the average (untraceable) primary production mix of an identical[8] commodity, the resulting PSC is equivalent to the byproduct-technology construct (BTC). In other words, BTC represents the secondary coproduction of a given commodity as avoiding the production of this same commodity by the average mix of primary producers, rather than, e.g., by a specific producer or the marginal producer (see Weidema 2003 on marginality and Majeau-Bettez et al. 2014 on traceability).

The LSA is at the foundation of the lump-sum construct (LSC).

4 Questions of attribution and of consequences

This section reviews the LCA literature in order to compile a list of desirable coproduction model characteristics for answering attributional and consequential research problems.

4.1 Desirable characteristics for coproduction modeling in attributional analysis

According to Heijungs (1997), "the attribution problem tries to give an answer to an accounting question," that is, "the question of which environmental problems are to be attributed to which economic activities." This definition is essentially preserved by UNEP and SETAC (2011), which define attributional studies as attempting "to provide information on what portion of global burdens can be associated with a product (and its lifecycle)." This is also in agreement with the notion of "accounting LCA" put forth by Tillman (2000).

Associated with the accounting question is the axiom of *100%-additivity*: the analysis should be such that, in theory, the "results of a separate analysis of all economic activities should add up to the result of an analysis of the total economic activity" (Heijungs, 1997). Logically, the analysis of the total economic activity should yield the total environmental impact of the economy, and therefore "if one were to conduct attributional LCAs of all final products, one would [ideally] end up with the total burdens worldwide."(UNEP and SETAC, 2011). In other words, the accounting rules of an attribution problem should not leave any significant[9] impact "unattributed," nor should it lead to a double attribution (double-counting) of impacts (Tillman, 2000). It then logically follows that any coproduction modeling in attributional analyses should be *conservative of burden* (characteristic a1): the model should calculate total burdens equal to that of the inventory from which it was derived when applied to this inventory's original final consumption (Brander and Wylie, 2011).

To build an epistemological foundation for ALCA, Heijungs (1997) presents the attribution question as an interpolation problem: a complete absence of human activity would lead to zero environmental impact, the total of all human activities leads to all environmental impacts, and, in between, a single activity can be ascribed a share of all environmental impacts. When representing activities as 'a share of the total', researchers clearly conceive each activity

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[8] In practice the concept of two products being *identical* is largely a question of level of resolution and the level of homogeneity of product groups, see Majeau-Bettez et al. (2016).

[9] In practice, all process-based LCAs necessarily omit some portion of the lifecycle, leading to so-called "truncation error." The ISO14041 (International Organization for Standardization, 1998) requires that such omissions be justified as insignificant, but the possibility of such a demonstration is put in question (Suh and Huppes, 2002). Truncation errors clearly introduce inconsistencies in attributional analyses and may be corrected through hybridization with EEIO analysis (Haes et al., 2004; Suh et al., 2004; Majeau-Bettez et al., 2011). Ekvall and Andrae (2006) explicitly identify hybridization as a means to better fulfill the requirements of ALCA.

as an integral part of the socioeconomic metabolism and not as a perturbation of it. This perspective on activities has lead multiple authors to define ALCA as a "static" (Heijungs, 1997), "steady-state" (Sandén and Karlström, 2007), "state-oriented" (Hospido et al., 2009), "descriptive" (Guinée, 2002), or "snapshot" (Levine et al., 2009; Pelletier et al., 2015) analysis. Since no activity is represented as changing (or having changed) the system, but rather as an inherent part of the *status quo*, we would argue that there is no room for counterfactual notions such as "avoided burden" or "substitution" in attributional coproduction modeling (characteristic a2) (Heijungs and Guinée, 2007). In other words, if an activity is fully integrated in a production-consumption system, there cannot be an "additional" or "unused" product left to avoid production outside the system boundaries (Brander and Wylie, 2011). In practice, this implies that production balance is respected (characteristic a3): if the *status quo* is not disturbed in the model, this model should be able to recalculate the original production volumes of the inventory from which it was derived when applied to this inventory's original final consumption (Kop Jansen and ten Raa, 1990; Majeau-Bettez et al., 2016).

The above desirable characteristics are not, however, sufficient to define ALCA, as the attribution of impacts cannot be done completely arbitrarily; it must follow the life cycle. Otherwise, nothing would prevent an ALCA from blaming all emissions of the economy on a single 'scapegoat' process and declare all other products free of environmental burden. Multiple authors therefore stress that the emissions of a given activity can only be attributed on a given product to the extent that this activity has "contributed to the production, consumption, and disposal of [this] product" (Weidema, 2014). In other words, an attributional study is defined as ascribing to a lifecycle only those environmental impacts that "[flow] to and from [this] lifecycle and its subsystems" (Ekvall et al., 2005). Responsibility[10] thus follows actual flows within a system description (Earles and Halog, 2011; Pelletier et al., 2015), and a reference flow should be held accountable (only) for "processes that are actually directly linked by (physical, energy, and service) flows to the unit process that supplies" it (UNEP and SETAC, 2011).

Consequently, attributional allocation or construct modeling should only associate an emission to a product if this emission is already connected to this product through production-consumption flows (characteristic a4). For example, in the simple system of fig. 2, an attributional assessment of coproducts k and k' cannot hold these products responsible for the emissions of industries M and N, as these industries do not contribute any reference flow to the lifecycle of these products. It then follows that neither k nor k' should be blamed for methane emissions from industry M in an attributional analysis of this system, regardless of which allocation or construct choices are made.

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[10] In the context of ALCA, responsibility can be understood in a strictly accounting sense, "without necessarily having any moral connotation" (Heijungs, 1997)

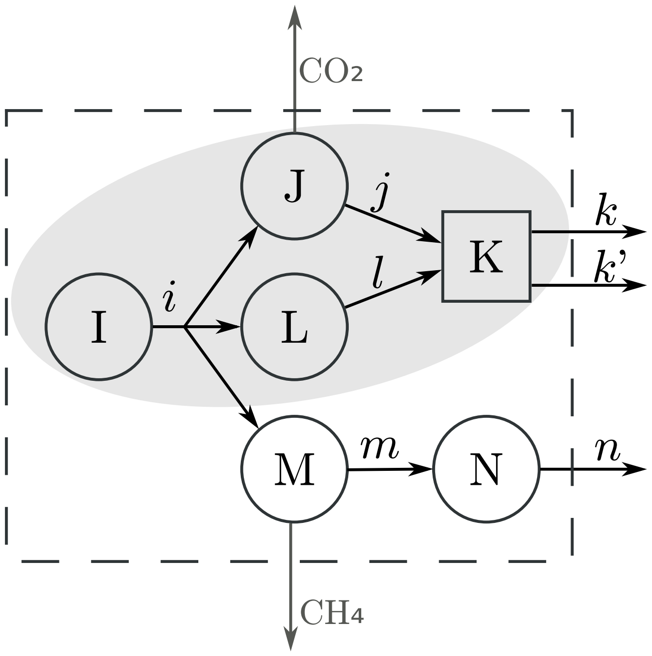

Figure 2: Attributional subsystems, with industries represented by capital letters, product flows by arrows with lower-case italic letters, the technosphere system boundary by a dashed line, and emission flows by gray arrows. The subsystem of industries contributing to the lifecycle of coproducts k and k' is highlighted in gray.

- Additivity
  - **a1** Coproduction modeling should be conservative of burden: preserve total burdens when model applied to total consumption
- Static, steady state description
  - **a2** Coproduction modeling should not rely on perturbation logic or counterfactual notions, such as "substitution," "avoidance," etc.
  - **a3** Coproduction modeling should not perturb the production balance
- Responsibility for impacts within the system follows flows of the different production chains
  - **a4** Coproduction modeling should not create links between emissions and activities that are not mediated by product or service flows

List 1: Desirable coproduction model characteristics for attributional analyses

4.2 Desirable characteristics for coproduction modeling in consequential studies

Instead of asking a question of attribution of impacts, one may ask how an isolated change in a system would alter these impacts: "Consequential LCA is defined by its aim to describe how environmentally relevant physical flows will change in response to possible decisions." (Finnveden et al., 2009).

Answering such a question necessarily relies on mechanisms of *causality* (Heijungs, 1997; Guinée, 2002). A consequential analysis strives to follow causal connections that link a perturbation to potential alterations in the technosphere's exchanges with the environment. This web of causal connections is extraordinarily complex (Guinée, 2001) and notably includes direct physical causation, market mediated effects, influence on capital investments and stock dynamics, and socially constructed causation and policy context (Sandén and Karlström, 2007; Pauliuk and Hertwich, 2016; Hertwich, 2014). No model can hope to fully account for all these causal connections, and therefore various CLCA approaches systematically introduce different sets of simplifying assumptions to make the model manageable by restricting it (Ekvall and Weidema, 2004; Weidema, 2003; Weidema et al., 2009; Dandres et al., 2011).

This predominant role of causation in CLCA determines certain desirable characteristics for the modeling of production technologies and commodity markets in situations of coproduction or multifunctionality. If the demand changes for a product, this can affect the coproducing activity, which may respond by changing its coproduction ratio; or it can affect the markets, which may need to accommodate an additional production of dependent coproducts; or it can affect both activities and markets to varying degrees.

To respect physical causation within coproducing activities, the choice of allocations or constructs should reflect the technological link between the coproducts (characteristic c1). Changing the demand for a coproduct will likely alter the inputs and outputs of the coproducing activity, and these changes will depend on the causal coupling between the coproducts, that is, whether the coproduction is a combined production, a partial-joint production, or a full-joint production (see Weidema, 2000). Furthermore, if the inputs and outputs of an activity are split between coproducts, this modeling should strive to reflect the technological requirements for the production of each coproduct (characteristic c2). In other words, if coproducts are modeled as being technologically independent, their respective standalone production functions should be technologically credible (examples in section 5.2).

Markets are represented as intermediate product nodes between industries in LCA and EEIO (Pauliuk et al., 2015), and their response to shocks have been extensively studied for consequential analyses.[11] Although the modeling of market mechanisms can largely be performed separately from allocation or construct modeling (Duchin and Levine, 2011; Marvuglia et al., 2013), coproduction situations impose constraints that should be respected to coherently model causation within markets (characteristic c3). Subsidiary products, whose supplies are free to adapt to changes in demand, are expected to compete differently on product markets than byproducts, whose production volumes are fixed by the demand for their associated primary products. Furthermore, in the case of exclusive byproducts, markets are expected to reflect a competition between products whose characteristics differ, which may therefore present limited intersubstitutability. In the example of fig. 1-VI, if the exclusive byproduct 'straw' is pushed on the market by an increase in wheat production, it will compete not against straw from primary production, but rather with firewood. As the characteristics of straw and firewood differ, they may not be perfectly substitutable, and the downstream consequences of this change in the mix of product markets should ideally be captured (as proposed by Weidema et al., 2013, section 11.7).

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[11] See notably literature on equilibrium and comparative advantage theories.

- Respect technological causation within activities:

  c1 The technological independence or interdependence (causal coupling) of coproducts should be preserved under the coproduction model (combined, partial-joint, or full-joint coproductions).

  c2 If inputs and outputs are split between coproducts, this coproduction modeling should reflect the technological requirements (causation) for the independent production of each coproduct

- Respect causation within product markets:

  c3 Market response should reflect the differing supply elasticities of coproducts and their competition with commodities from other (primary) productions, taking into account differences in product characteristics that can affect their intersubstitutability.

List 2: Desirable coproduction model characteristics for consequential analyses

5 Concordance analysis between coproduction type, model, and research question

This section assesses to what extent the different coproduction models (fig. 1) conform to the desirable characteristics for ALCA and CLCA (lists 1 and 2) when applied to different types of coproduction situations (table 1), as summarized in table 2.

Table 2: Concordance of disaggregation, system expansion, and allocation or construct models [rows] with attributional or consequential research questions [columns] when applied to different types of coproduction situations [comments in bottom notes]. A check-mark (✓, in blue) indicates that no inconsistency is introduced, whereas any other text (in red) indicates the limits to the coproduction model and the desirable characteristics that it violates. "a.m.p.p." = "average mix of primary producers"

Procedure / Models	Attributional	Consequential
Sub-division/disaggregation	✓	✓
Classical system expansion	✓	✓
Partition (PA, PC, ESC, ITC)	✓	†, c2
Alternate-Activity (CTC[***], AAA, AAC)	✓[*]	✓[†,**]
Substitution (PSA, PSC)	a1, a2, a3, a4	✓[‡]
of identical[***] commodity from a.m.p.p. (BTC)	a2, a3, a4	✓[‡]
Lump-Sum (LSA/LSC)	a1,a3	c1, c2, c3

[*]: Violates a4 if it introduces negative flows.

[**]: Introduction of negative flows indicates an implausible technology, violating c2.

[***]: Not applicable to exclusive secondary products.

[†]: Violates c1 (and therefore c3) if applied to anything other than a combined production.

[‡]: Violates c1 (and therefore c3) if applied to anything other than a full-joint production.

5.1 Concordance with attributional questions

Both classical system expansion and disaggregation are fully compatible with all desirable characteristics of an ALCA regardless of the type of coproduction to which they are applied. We also find PA to be fully aligned with all desirable characteristics of the attributional perspective.

Substitution-based models, on the other hand, contradict most desirable characteristics of an attributional question. They are not production-balanced (characteristic a3), as applying these models to the original consumption level does not result in the original production volume (Kop Jansen and ten Raa, 1990; Majeau-Bettez et al., 2016). This modeling has therefore been interpreted with a disruptive or dynamic reasoning, which contrasts with the state-oriented, descriptive nature of ALCA (Heijungs and Guinée, 2007) (characteristic a2). This disruption in the product system is reflected in the exchanges with the environment. Substitution modeling does not generally conserve total burdens (characteristic a1), as applying these models to the original consumption does not recalculate the original emissions (Brander and Wylie, 2011). BTC constitutes an exception in this respect, however, because the perfect substitution of an identical commodity that originates from the average mix of primary producers[12], as assumed by this construct, necessarily conserves total environmental burdens (Suh et al., 2010). This special case of substitution is only applicable to situations without exclusive secondary products. Furthermore, the attribution of burden does not exclusively follow observable physical and service flows in substitution models; the lifecycle impacts of primary products depend not only on the activities physically involved in their production chain, but also on activities with which their secondary products compete, violating characteristic a4.

Just like substitution models, lump-sum models violate the criterion of production balance (characteristic a3) (Majeau-Bettez et al., 2014) and conservation of burden (characteristic a1).

The AAA can respect all desirable characteristics of an attributional study *under certain conditions.* It is conservative of burden and production balanced, and it has a clear interpretation as a static, descriptive model (Suh et al., 2010). However, assuming a production technology for each secondary product may or may not introduce requirements and impacts that occur outside of these products' value chains into their lifecycle descriptions. For example, in fig. 1, the assumption that the secondary production of straw is technologically similar to "Hay Farming" allocates to it a share of the requirements (j and k) of the multifunctional activity "Grain Farming," in accordance with characteristic a4. Conversely, with the system in fig. 2, if the requirements of coproducing activity K were split with AAA by assuming requirements for the standalone production of k' based on the technology for the production of n by industry N, this would ascribe requirements and emissions to k' that are *not* found in its production chain, thus violating characteristic a4. As illustrated in the supporting information, such an allocation would ascribe to the production of k' direct requirements of m (a requirement that industry K does not have) and indirect emissions of methane (an emission that is not found in its lifecycle). To maintain production and burden balances (characteristic a1), primary product k would then be ascribed *negative* requirements of m, eventually leading to indirect negative emissions of methane, both of which are, of course, also absent from its lifecycle. With such negative coefficients, we are getting dangerously close to the aforementioned "scapegoat problem." In fact, if alternate-activity models (AAA, AAC, CTC) lead to negative coefficients, this is a certain indicator that secondary products have been ascribed requirements that are not found in their inventory, thereby violating characteristic a4. This provides further justification for the efforts by multiple authors to avoid negative values arising from CTC (as reviewed by ten Raa and Rueda-Cantuche, 2013).

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[12] or is untraceable to any specific producer, see Majeau-Bettez et al. (2014) on traceable and untraceable inventories

5.2 Concordance with consequential questions

Whenever applicable, both disaggregation and classical system expansion are consistent with the desirable characteristics of CLCA.

In contrast, PA splits requirements based on other criteria than those aimed at modeling valid technological recipes for each coproduct, which hinders its ability to capture the consequences of a change within coproducing activities (characteristic c2). In addition, partition-based models allow for the independent production of primary and secondary products in any ratio, which could be consistent with a consequential description only in cases of (near) combined production (characteristics c1).

LSA essentially abolishes secondary products, which fails both to respect the causal coupling between coproducts (characteristic c1) and to generate production recipes that are realistic (characteristic c2).

Both PSA and AAA may model technologically credible production functions and markets, depending on the type of coproduction to which they are applied.

Substitution models impose a fixed ratio between primary and secondary product. With such models, an additional demand for a primary product automatically forces a proportionate production of its coproducts, which in turn leads to the displacement (i.e., substitution) of other productions. This approach can approximate causation mechanisms in full-joint productions (with byproducts). If applied to coproducts whose production volumes are wholly or partly independent, however, this model disrupts the relation between coproducts and imposes excessive constraints on markets, in contradiction with consequential perspective. In the case of a farmer running a touristic accommodation service on site (subsidiary coproduct), it would be unjustified to assume that an increase in the agricultural production will automatically lead to a proportionately greater number of guests, as the two are not technologically coupled (characteristics c1). Consequently, it is not appropriate to represent the offer of on-site accommodation as inelastic to changes in demand, as is implied by PSA, potentially leading to misrepresentation of market dynamics, such as the competition with conventional hostelry (characteristic c3).

By assuming the requirements of an alternate stand-alone activity for each secondary production, AAA represents secondary coproducts as independent from their primary coproduct, with their own independent requirements and production volumes. This can only constitute a valid consequential model if applied to a combined production (with subsidiary coproduct). In all other cases, this disrupts the relation of dependence between coproducts (characteristic c1). For example, an AAA would model straw and grain production as independent, and it would then be possible to produce more straw in the 'Grain Farming' industry without producing more grain, and *vice versa*, which would not reflect physical causation. This would also likely fail to capture market dynamics (characteristic c3), since a byproduct is expected to be inelastic to change in demand.

Even when applied to combined productions, AAA is not guaranteed to yield technologically credible descriptions for the independent production of all coproducts (characteristic c2). This depends notably on the existence primary productions that can serve as good technological proxies for the production of each secondary product. The credibility of these technological assumptions may prove difficult to evaluate, but the introduction of negative flows by AAA does provide clear indications of an implausible production technology.

Table 2 then questions the simple adequation between substitution and CLCA. In fact, *this table combines three longstanding insights from the LCA and IO literature to form a clear recommendation for internally consistent coproduction modeling in consequential analyses:* [i] combined production is preferably disaggregated with additional data whenever feasible (ISO 2006, Weidema 2000), failing which [ii] AAA and its associated constructs (including CTC) seem better aligned with combined productions and subsidiary coproducts (Konijn 1994, as cited in Heijungs 1997; and European Commission 2008), whereas [iii] full-joint production and byproducts are rather best represented by substitution models (including BTC) (Weidema, 2003; European Commission, 2010, section 7.2.4.6).

6 Discussion

6.1 The gray zone between combined and full-joint production for CLCA

If, from a consequential perspective, substitution modeling can be fully consistent only in cases of full-joint productions, and if AAA can be fully consistent only in the case of combined coproductions, the consequential description of partial-joint productions is left without a clearly favorable allocation model. These simple allocation and construct models seem incapable of capturing causation in such complex, partial technological linkages.

In the case of the coproduction of milk and meat by the dairy sector, for example, assuming that an increase of milk consumption would force upon the market a proportionate increase in cattle meat — as is implied by substitution allocation— constitutes an oversimplification, since farmers have some measure of control over the ratio between these products (United Nations, 1999). Conversely, modeling the production of milk as technologically independent from the production of meat in the dairy sector — as is implied by AAA— will lead to unrealistic technology descriptions because of the important common costs of these coproducts and gains in efficiency[13] that stem their coproduction (Weidema, 2000).

Production requirements are not expected to scale linearly to an alteration in the supply ratio of coproducts, as it likely will effect the efficiency gains that stem from their partial-joint production. Such non-linear behaviors are difficult to accommodate within a linear LCA or IO framework. This issue may prove rather common in practice, since most coproductions are deemed to fall somewhere between a full-joint production and a combined production (European Commission, 2008; Suh et al., 2010). Treating all secondary productions as being either completely inelastic to change in demand (byproduct, PSA) or fully elastic (subsidiary product, AAA) therefore constitutes a crude simplification (Guinée, 2002; Ekvall and Weidema, 2004).

Avoiding this simplification and adequately representing non-linear responses due to partial causal coupling requires the use of more sophisticated engineering and biochemical process models (Nakamura and Kondo, 2002). Two strategies in the literature exemplify the integration of these non-linear consideration in a traditionally linear LCA or EEIO framework.

Azapagic and Clift (1995) analyzed the coproduction of various hydrocarbons through naphtha cracking. The non-linear relations that relate coproduction ratios to cracking conditions (and requirements) are well understood, and the consequences of marginally increasing the yield of propene, for example, can then be isolated through the partial derivative of these functions with respect to propene output. In the case of marginal changes that are "sufficiently small to be approximated as infinitesimal," their effect on a multifunctional process can thus be isolated and linearized around the initial state without loss of physical credibility (Azapagic and Clift, 1999). This description of the changes in requirements and emissions can then be inserted as production functions in a Leontief or a linear programming framework to analyze the lifecycle consequences (Weidema, 2000; Duchin and Levine, 2011), as further detailed by Azapagic and Clift (1998).

For the assessment of larger changes, however, linearization would likely not reflect physical causality (Azapagic and Clift, 1999), and a deeper integration of biochemical or engineering models in lifecycle calculations would be required. An example of such an integration is the

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[13] cf. economies of scope (Panzar and Willig, 1981)

Waste IO model by Nakamura and Kondo (2002), which iterates between two representations of the same waste sectors, one in a physical IO model and another in an engineering model. In this representation, waste treatment sectors can be seen as multifunctional, simultaneously treating multiple waste types. The linear IO model calculates a first estimate of emissions and waste volumes for the economy under a certain scenario. These waste volumes are then passed as parameters to a model that takes into account the non-linear effects of waste ratios on the requirements and emissions of treatment facilities. These adapted requirements and emissions then serve to update the technological description of waste treatment sectors in the IO model, which then recalculates total emissions and waste production volumes for the economy, which may in turn be re-inserted as parameters in the engineering model, and so on until the two models converge on a representation of multifunctional waste sectors that is both consistent with the scenario and technologically credible (Nakamura and Kondo 2002, figure 1). In this manner, the model is able to capture the consequences of a change in the outputs of a partial-joint multifunctional process, respecting all desirable characteristics for consequential multifunctional modeling in list 2.

The representation of loose technical coupling is clearly data intensive, and the dynamic combination of Leontief models with sector-specific engineering models remains rare and complex. Further research is therefore warranted for the most appropriate representation of partial-joint coproduction in LCA and EEIO. In the meanwhile, it may prove necessary to resort to a mix of PSA and AAA in consequential analyses, especially for large generic datasets like the consequential version of Ecoinvent (Wernet et al., 2016; Steubing et al., 2016). Efforts should then be made to determine whether each coproduction is closer to a full-joint production or to a combined production, in order to minimize the consequences of this simplifying assumption. The importance of these simplifying assumptions may be assessed through sensitivity and uncertainty analyses (see Jung et al., 2013; Mendoza Beltran et al., 2015), so as to determine whether investing research resources into more refined coproduction modeling will significantly improve the final results.

6.2 Limitations and caveats

The analysis in table 2 focuses solely on the relation between coproduction, allocation model, and attributional or consequential research questions. Many other modeling considerations must be taken into account to asses the internal consistency of attributional or consequential analyses. In practice, studies with a consequential aim vary greatly in terms of scope, modeling complexity, transparency and simplifying assumptions (as reviewed by Earles and Halog 2011; compare method by Weidema 2003 and Dandres et al. 2012). The same can be said of ALCAs. This study did not aim to review or evaluate how ALCAs and CLCAs are applied. It rather strove to analyze the level of coherence between key modeling choices and defining research objectives. We have therefore focused on desirable model characteristics that can be mostly inferred *a priori* from the type of research question asked.

Our formal analysis leads to the identification of clear potential inconsistencies, but it cannot determine preference between models when more than one is fully consistent with the research question type. For example, although this analysis points to situations where PA is the only applicable model, but it cannot offer guidance as to which property should guide the partition (monetary value, mass, exergy, and so on). This would depend on the rationale behind the attributional analysis (Ekvall et al., 2005; Pelletier et al., 2015).

Similarly, in cases where both PA and AAA are equally applicable to a given coproduction for ALCA, our concordance analysis does not dictate which should be preferred. We would venture, however, that if a coproduction is close to being a combined production, and if a credible technology proxy is available, then the AAA may be viewed as closer to a form of disaggregation ("proxy-based disaggregation") and may therefore be preferred over PA. Such a proxy-based disaggregation could be viewed as better "reflect[ing] the underlying physical relationship between" the main and (near) subsidiary product, as recommended by the ISO14044 (ISO 2006). Further research is required on the relation between AAA and disaggregation, and also on the topic of "partial disaggregations," or "virtual sub-division" (European Commission, 2010, section 7.4.2.2).

6.3 Synthesis of results and research avenues

Our findings confirm that the prevalent dichotomy between partition and 'system expansion' is overly limiting and sub-optimal for answering attributional and consequential lifecycle questions.

For attributional questions, we find that a combination of partition and alternate-activity models proves most consistent (table 3, second column). Alternate-activity models should only be applied when they do not lead to negative coefficients, as the introduction of negative flows by this model is inconsistent with one of the defining characteristics of ALCA (characteristic a4). In practice, this is likely to limit the application of AAA to situations of near combined productions for which a good technological proxy is available. Our analysis of ALCA is therefore well aligned with Gigantes (1970), Bohlin and Widell (2006), and Smith and McDonald (2011), who argue for the combination of ITC and CTC, which are based respectively on PA and AAA, to avoid negatives in IO tables.

Table 3: Result Summary: potentially suitable allocations and constructs depending on coproduction types and research questions

Type of coproduction	Attributional question	Consequential question
Full-joint production	PA/PC, AAA*/AAC*	PSA/PSC
Partial-joint production	PA/PC, AAA*/AAC*	
Combined production	PA/PC, AAA*/AAC*	AAA**/AAC**

*: Violates desirable attributional characteristic a4 if it introduces negative flows.
**: Negative flows indicate a violation of desirable consequential characteristic c2.

For consequential questions, we find that the combination of substitution applied to (near) full-joint productions and alternate-activity models applied to (near) combined productions would fit best (table 3, last column). This is in line with ten Raa and Chakraborty (1984) and Londero (1999), who recommend a combination of CTC and BTC to represent different types of coproduction. This mix of models should ideally be based on an assessment of the level of technological coupling between coproducts, but it may be at least partly automated based on the generation of negative coefficients by CTC. Whilst negative flows arising from substitution allocation have a clear modeling role (namely, the substitution of primary productions) (Suh et al., 2010), the negative coefficients arising from AAA can typically be interpreted as signs of sub-ideal technology assumptions for stand-alone production (Viet, 1994; Londero, 1999; Almon, 2000; ten Raa and Rueda-Cantuche, 2013) (see supporting information (SI) for further discussion of negative flows).

In contrast to Kop Jansen and ten Raa (1990), we do not find a universally preferred construct; the choice of construct depends on the attributional or consequential question at hand, and on the type of coproduction present in the inventory. From our analysis it appears that the CTC, which has been promoted as axiomatically superior, is only clearly advantageous when applied to combined coproductions with ordinary (non-exclusive) subsidiary coproducts.

As AAA and associated constructs rely on assumptions of technological similarities between secondary productions and standalone primary productions, the evaluation of these assumptions will remain a scientific challenge. One approach to evaluate the validity of these assumptions relies on the careful examination of the technology of the remaining primary production. Beyond merely searching for the presence of unwarranted negative coefficients, efforts should be made to determine whether this residual technology is viable and whether it resembles existing productions.

The present analysis indicates that the different allocation and construct models are too simplistic to adequately represent intermediate levels of technological dependence between coproducts from partial-joint productions. Especially since reaping benefits from coproduction and pooling infrastructure requirements is at the core of industrial ecology and industrial symbiosis (Chertow, 2007), there is a need for lifecycle tools that can account for coproductions with loose technological coupling. Moving beyond linear allocations and constructs and capturing the non-linear adaptation of coproducing activities to varying demand levels therefore constitutes the next frontier in value chain and lifecycle modeling.

Acknowledgments

For their challenging and inspiring discussions, we wish to thank Sangwon Suh and Bo Weidema. We also thank Christine R. Hung for language editing on an early version of this manuscript. The authors remain solely answerable for the content of this study.

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