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Relevance of attributional and consequential life cycle assessment for society and decision support

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Life cycle assessment (LCA) is an essential tool for assessing the environmental impact of product systems. There are two main types: attributional LCA (ALCA), which assesses the global impact share of a product's life cycle, and consequential LCA (CLCA), which evaluates the consequential impact of a decision. In our analysis, we explored the relevance of these types for society and their ability to aid decision-making. This analysis builds upon existing literature and incorporates two ideological and three pragmatic criteria. First, when it comes to realistic modeling as desired in the context of sustainable development, in theory, CLCA attempts to model realistically, whereas ALCA falls short to a certain degree because of conceptual rules, e.g., artificial splitting of co-product processes. Concerning the second criterion of alignment with ethics, CLCA completely aligns with consequential ethics, where an action is judged based on its consequences. This alignment of CLCA makes it undoubtedly relevant in a world where we aim to obtain favorable consequences in the future, e.g., meeting sustainability goals. ALCA is only partially consequential, as it is restricted by conceptual rules relating to deontological ethics and, for example, covers the relative past of the product. Since deontological ethics, i.e. judging an action based on its alignment with rules, is generally relevant for our modern human society, there is room for complementarity in ethical relevance between ALCA and CLCA. However, the conceptual rules of ALCA (e.g., additivity) and their relevance have not been accepted by society. As a result, ethical acceptance of ALCA is still required. In the context of decision support, CLCA evaluates the consequences of decisions, while ALCA encompasses the approval and sharing of potential responsibility for the environmental impact throughout the life cycle of the product associated with the decision. We also highlight the unique valorization of Organizational ALCA, which entails the aforementioned aspects for the organizations responsible for the product. Concerning the three practical criteria, the following conclusions were drawn. Although ALCA has received the most attention in terms of standards, only CLCA can currently be consistently conducted in a reliable manner. This is because the current life cycle impact assessment methods applied in ALCA do not yet partition environmental multi-input processes. CLCA should be given greater prominence in standards. Furthermore, the complexity and uncertainty associated with modeling may often be only slightly higher for CLCA than for ALCA, mainly due to the consideration of change resulting from a decision. However, both ALCA and CLCA modeling may be similarly complex and have equally high levels of uncertainty as both methods encompass past and/or future projections (e.g., prediction of future background processes). Finally, ALCA modeling may be viewed as a practical approximation of CLCA, but the current CLCA models are more suitable for studying consequential effects. As CLCA modeling and databases continue to improve, this distinction will become even more pronounced.

KEYWORDS

life cycle assessment, decision support, sustainability, consequential life cycle assessment, attributional life cycle assessment, environmental impact, life cycle

1. Introduction

Life cycle assessment (LCA) serves as a valuable tool for assessing the environmental impact of human/industrial product systems. In the literature, two specific types of LCA, namely attributional and consequential LCA, exhibit notable differences. These two types are the focus of this study. However, the manifold definitions and interpretations of these two types, necessitate clarification. To achieve this, we build further on the argued selection of definitions, with specific conceptual characteristics and imposed modeling restrictions, as recently brought forward (Schaubroeck et al., 2021b).

Based on their selected definitions of UNEP-SETAC (Sonnemann et al., 2011; UNEP-SETAC, 2011a), consequential LCA (CLCA) "attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product)", with all further specifications being logically and unequivocally derived from it. Attributional LCA (ALCA) "attempts to provide information on what portion of global burdens[1] can be associated with a product (and its life cycle)" based on the following additional conceptual rules: the product system, as a product's life cycle, "contains processes that are directly linked by physical, energy, and service flows to the unit process that supplies the functional unit or reference flow" (the latter being the amount of product that is studied), and "in theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide", according to UNEP-SETAC (Sonnemann et al., 2011; UNEP-SETAC, 2011a). However, the latter document lacked a specification of what "final products" entail, as they may be considered the same as finished products. Schaubroeck et al. (2021b) introduced a definition for final product ("a product that is directly consumed by humans and not used in the life cycle of another product") that made the concept of additivity consistent. As pointed out by the latter authors, all these rules are at a conceptual level that indirectly imposes modeling restrictions. They are not modeling constraints due to practical limitations (e.g., lack of data, information, models, time, and so on). Throughout the rest of the manuscript, when we use the word "rules", we mean conceptual rules.

The difference between ALCA and CLCA is briefly exemplified for a product in a store. ALCA covers the environmental impact of the product life cycle of that product, covering all its interlinked processes, whereas CLCA would cover the environmental impact of, for example, the decision to buy that product. These systems differ substantially. For example, while ALCA would cover the past production of that product, CLCA would not, as it cannot be influenced by the purchase since what happens in the past before a decision cannot be influenced by that decision (Schaubroeck et al., 2021b). We refer to the study by Schaubroeck et al. (2021b) for a further explanation of the concepts, and an overview is presented in the final table of that study.[2] We strongly encourage readers to read that study first, as our article follows up on it. Despite the argued elaboration on ALCA and CLCA by Schaubroeck et al. (2021b), recently, several authors (Ekvall, 2019; Finnveden et al., 2022) have considered other definitions of ALCA and CLCA (Finnveden et al., 2009) again, despite the preceding publication of the study by Schaubroeck et al. (2021b). The same also goes for the study by Bamber et al. (2023). Having multiple definitions circulating in the community leads to other claims and evaluations of ALCA and CLCA, particularly in the case of the recent study by Finnveden et al. (2022). This conundrum prompted us to better evaluate their particular sets of definitions in this study compared to those of UNEP-SETAC (2011a). See Section 1.1 for an elaboration on this matter.

Returning to this study's main topic, we focus on the relevance of ALCA and CLCA for society, which Schaubroeck et al. (2021b) did not address. Foremost, ALCA and CLCA answer different questions, but to what extent are these the actual questions that society poses in different contexts? Moreover, the actual available modeling frameworks and their applicability should also be evaluated in terms of concreteness and practicality. In search of high-value methods for society, we need to evaluate them concerning their usefulness, which is also the case for methods assessing sustainability. Society is here understood as "a large group of people who live together in an organized way, making decisions about how to do things and sharing the study that needs to be done" (Cambridge English Dictionary, 2019). Given the global

1 As pointed out by Ekvall in personal communication with him, the word "burden" might be only focused on negative/damaging impacts. The word "environmental impact" would have been better, but we presume that the latter is implied.

2 It should be noted that for CLCA, multifunctionality issues are to be addressed by "co-product effects" in general, as pointed out explicitly in the literature (Schaubroeck et al., 2021a, 2022), whereas this was vaguely described by Schaubroeck et al. (2021b).

nature of sustainability issues (Liu et al., 2015), it is relevant to consider the global society. We need to look beyond agreements within the LCA community or ISO standards and regard global societal demand as such, without bias from individual perspectives. Hence, we cannot only consider LCA methods to be relevant because they have been agreed upon by the small (scientific) communities behind them or the preferences of individuals; they should instead be compared with their validity and relevance in light of a global context (e.g., global ethics), which is within the focus of this study. Other studies have evaluated separate aspects and are presented in this manuscript, but almost none consider a broad overview and review of different evaluation aspects, implying that these studies do not specify a set of evaluation criteria beforehand. The two studies that do are those by Ekvall et al. (2004) and Ekvall (2019), which will be discussed in detail, particularly in Section 2.3. To summarize, the goal of this study is to value these two methods, attributional and consequential LCA, in light of their societal relevance concerning sustainability assessment methods based on the literature and also to elaborate the analysis further. Although our manuscript is a review, there are considerable novelties, and these are summarized in a table provided as Supplementary material.

Structure-wise, in the second section of this manuscript, we argue for the selection of certain evaluation criteria. In the third section, we evaluate attributional and consequential LCA according to these criteria. In the end, in Section 4, a conclusion and a further outlook are presented. It is worth noting that a preprint version of this manuscript was shared online before submission (Schaubroeck, 2022a).

1.1. Pinpointing issues with another set of ALCA and CLCA definitions

As yet specified, definitions for ALCA and CLCA have been thoroughly selected and argued by Schaubroeck et al. (2021b), on which we build further in this evaluation article. The main selected definitions in the latter study are those presented in a UNEP-SETAC (2011a) report, with as the chief selection argument the global representativeness of this report by the many scientists involved in writing and reviewing it and the bodies behind it, particularly a United Nations institute (keeping in mind that the UN is the most globally representative intergovernmental institute), illustrating a larger consensus and authority. Nevertheless, there still seems to be an adherence to the definitions of ALCA and CLCA by Finnveden et al. (2009), who in turn, as explained further on, loosely based them on the definitions by Curran et al. (2005). Recent authors (Ekvall, 2019; Finnveden et al., 2022) have used these definitions, and this is why we assess them first.

According to Finnveden et al. (2009),

- Attributional LCA (ALCA) "is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems", which is quite different from the UNEP-SETAC (2011a) report followed in this study, and
- Consequential LCA (CLCA) "is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions", which is very similar to the UNEP-SETAC (2011a) report followed in this study.

The main issues with the definition selection and different characteristics (mainly for ALCA) are as follows:

1) The choices of the definition by those authors are not or minorly argued. Finnveden et al. (2009, 2022) did not argue their selection. It should be noted that Finnveden et al. (2022) referred to Finnveden et al. (2009) as the main reference for their definitions. Ekvall (2019) mentioned that it is a preference and also that there are a high number of citations of the review by Finnveden et al. (2009). However, the latter study is a general review, which people have cited for many reasons. Moreover, the definitions in the study by Curran et al. (2005) were authored by three people and derived only from an international workshop on electricity data with many participants and no global body. This all falls short compared to the thorough selection of definitions by Schaubroeck et al. (2021b) based on various criteria, with a realization of the need for large consensus and authority behind a definition, as is most the case for the UNEP-SETAC (2011a) report.
2) The lack of further specification of "life cycle" and system characteristics in the case of ALCA in the study by Finnveden et al. (2022) constitutes a major and crucial lack of specificity that would normally characterize what ALCA entails. This absence of clarity leaves their ALCA definition open to many interpretations. Hence, one could even argue that "the system caused by a decision" constitutes as a product's life cycle, thereby confusingly categorizing CLCA as a type of ALCA. To the contrary, In the UNEP-SETAC (2011a) report, the definition of the product life cycle is well specified ("contains processes that are directly linked by physical, energy, and service flows to the unit process that supplies the functional unit or reference flow"), making it unique and of added value. It should be noted that within the general context of LCA (not separately for ALCA), Finnveden et al. (2009) specify LCA and the product life cycle as follows: "Life Cycle Assessment is a tool used to assess the potential environmental impacts and resources used throughout a product's lifecycle. This life cycle encompasses various stages, starting from raw material acquisition, through production and use phases, and ending with waste management (ISO, 2006). The waste management phase includes disposal as well as recycling". However, then there is no difference between ALCA and LCA, but CLCA could, in this case, not be an LCA. The latter is because the consequences of a decision will not necessarily cover a product's life cycle (Schaubroeck et al., 2021b). Finally, this general product life cycle definition does not specify which types of relationships are covered between processes that constitute the life cycle, whereas this is specified for ALCA in the UNEP-SETAC (2011a) definition: physical, energy, and service flows. These consistency issues and lack of specification, relate to the issues raised by Schaubroeck et al. (2022) with regard to the ISO 14040–14044 standards. In the latter study, the authors also present solutions, of which the most advised ad

interim is a more open and general LCA framework, where a "product system comprises all processes interrelated with the object of study as specified in the goal". This framework covers distinguished ALCA and CLCA concepts as types, following the UNEP-SETAC (Sonnemann et al., 2011; UNEP-SETAC, 2011a) definitions of these. Moreover, what "subsystems", as used in the ALCA definition of Finnveden et al. (2009), specifically imply, is nowhere addressed.

3) Furthermore, the product life cycle definition and related specifications should ideally also constrain the selection of multifunctionality solutions and modeling (Schaubroeck et al., 2021b), which is not possible in their case. As explained by the latter authors in their study, concepts can restrict modeling choices through their conceptual rules. See, among others, Figure 1 in their study. When following the UNEP-SETAC (2011a) definitions, partitioning is imposed within ALCA because of its additivity of final product requirements ("attempts to provide information on what portion of global burdens [see text footnote 1) can be associated with a product (and its life cycle)"]; the additivity aspect in the goal and scope necessitates and argues the use of partitioning (following well the notion that methodological choices should align with goal and scope) (Schaubroeck et al., 2021b). More precisely, concerning additivity, to ensure that the sum of ALCAs where the separate coproducts of a multifunctional system are considered, is the same as an ALCA where all coproducts are considered together, multifunctional processes must be split consistently using the same partitioning key. See also the explanation in Section 3.5 of the study by Schaubroeck et al. (2021b). As explained above, partitioning is a non-scientific procedure that can be best explained by a certain delimitation in the goal and scope, if not for practical limitations. Originally, Heijungs (1998) introduced a plausible need for additivity as a delimitation in the goal of LCA to argue for linearity and later partitioning. Nevertheless, this additivity requirement and its implications were only inherited by attributional LCA. Another adequate justification for using partitioning to address multifunctionality would be the practical limitation of addressing multifunctionality in another way, particularly when a database is missing; it provides another way of multifunctionality handling for the background system (it is worth noting that these exist, namely the consequential version of ecoinvent and that of EXIOBASE). However, such a practical limitation is not a conceptual rule and is irrelevant in a theoretical discussion. The ISO 14040–14044 standards do not mention this additivity requirement or the type of modeling that should be used. The effect of substitution and possible other co-product effects (Schaubroeck et al., 2022) are also excluded in ALCA because of (a) its non-additive nature, (b) it is a market process (dependent on human behavior) beyond physical flows and services, and (c) it is counterfactual, which ALCA is not for the product system. These argued characteristics are an advantage of the clear specification of the UNEP-SETAC definitions, which is not the case for the ALCA definition of Finnveden et al. (2009). Their definition of ALCA thus also lacks specificity on how to address multifunctionality and modeling consistently compared to LCA in general.

4) Strikingly, the study by Curran et al. (2005), which was cited by Finnveden et al. (2009) as a reference for their definitions, has presented another definition of ALCA, also implicating another specification for the product life cycle, specifically stating, "The attributional approach to LCI serves to allocate or attribute, to each product being produced in the economy at a given point in time, portions of the total pollution (and resource consumption flows) occurring from the economy as it is at a given point of time" and "The rules used to define which processes are in or out of the system in attributional modeling are those based on an observation of how materials and energy are flowing in the system at the given point of time". Notice the focus on using boundaries based on a certain point in time. This seems to not have been considered at all in the studies by Finnveden et al. (2009, 2022) and Ekvall (2019), particularly not in the definition of ALCA. This means that the reference to Curran et al. (2005) seems not correct for ALCA by Finnveden et al. (2009), and the only ones that explicitly underscore the definitions of Finnveden et al. (2009) are its authors. Alternatively, the definitions of Finnveden et al. (2009) seem to align completely with those presented by Ekvall et al. (2004).

5) The consideration of "environmentally relevant flows" in their ALCA definition and not just flows, in general, implies an ambiguous specification of relevance when applying the definition. When is a flow considered "environmentally relevant", and when not? It would seem better to leave "relevant" out of the definition than have such an unsubstantiated notion. Moreover, the impacts of the flows (e.g., global warming potential) should finally be assessed in an LCA study, not just the flows (e.g., CO_2 emissions) themselves. This perhaps coincides with a probably limited interpretation that attributional and consequential only relate to the life cycle inventory (LCI) specification. However, attributional and consequential typology also have implications for life cycle impact assessment (Schaubroeck et al., 2021b). To further underscore this, the terminology is attributional LCA, not attributional LCI.

6) The main criticism of Finnveden et al. (2022), with regard to the definition of ALCA by UNEP-SETAC (2011a), relates to the part that "In theory, if one were to conduct attributional LCAs of all final products, one would end up with the total observed environmental burdens worldwide". Finnveden et al. (2022) mentioned that "*One example of this could be when the 100 % rule is explicitly only for 'final products', where 'final products' are defined 'as a product that humans directly consume and not used in the life cycle of another product' [4]. Interpreted in this way, the 100% rule is only relevant for 'final products' and not necessarily for other types of products. In practice, it may be difficult to identify final products based on this definition. An LCA practitioner is free to choose the product under study, and most LCAs are not of final products, making the 100 % rule less relevant.*" There are two issues with the latter statement. First, the focus on final products is explicit in the UNEP-SETAC (2011a) report, not just an interpretation of the general 100% rule. Second, the validity of the ALCA definition is at

a theoretical level, not a practical one. Indeed, it might be difficult to define when a product is final or not in practice. However, it is also similarly difficult to, in practice, cover all processes of a product system, whereas it is dictated in theory. Building further on the elaboration on specifying final products in Section 3.4 of Schaubroeck et al. (2021b), in the worst case, when a product is both final and non-final at the same time, it might even be partitioned in shares, like the way partitioning of processes is allowed in LCA, with the exclusion of CLCA. Furthermore, it should be noted that ALCA-results of final (e.g., driving a car for the joy of it) and non-final products (e.g., gasoline) can be added in practice, as long as not the same products are used in both, e.g., not the same fuel that is used for that instance of driving. This does not concern the products in general, e.g., not that fuel cannot be used in final products but that it is not a specific fuel amount considering its unique identity. If it were the same, it would imply that the unique product is considered multiple times, in this case, a specific fuel amount, and there is double counting. It is worth noting that this additivity holds for the products, not their functionality. In other words, it is not an issue that a product can have multiple (final) functionalities.

In addition, we will also touch upon the definition of ALCA as a snapshot for a specific point in time, as presented by Curran et al. (2005) and recently still similarly considered by, for example, Bamber et al. (2023). First, there are some similar issues with these definitions: (a) the lack of argument in their selection and lack of representativeness compared to those of the (UNEP-SETAC, 2011a) and (b) the lack of delimitation of how multifunctionality should be addressed. There are some additional specific issues:

- It is not representative of reality to consider a specific point in time for a system that constitutes a collection of processes that are linked through flows, as these processes and their totality are inherently spread over time in reality. For certain processes, it might be quite straightforward that they will occur quasi at the same time point, e.g., electricity production and consumption, but for others, this is not the case, e.g., the production of a car and its usage over multiple years. See, among others, the study by Pigné et al. (2020). Probably, this delimitation to a point in time can again be viewed as a conceptual rule and further levels of artificial accounting on a theoretical level, but this can be questioned regarding its usefulness and acceptability. We noticed that in the study by (Curran et al., 2005) in other sections of their manuscript, "chosen temporal window" was inconsistently used instead of a point in time. If it is a chosen time window, this already allows for a more realistic spread of processes over time. However, this should not be chosen or prefixed, leading again to issues of possibly misrepresenting reality when actual product system processes occur before or after that time window, indicating it to be a conceptual rule.
- The second argument deals with the non-alignment of this ALCA definition with the main definition of a life cycle in the amended ISO 14044 (ISO, 2020): "consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal". First of all, "consecutive" implies a distribution over time. Hence, the ALCA definition, where a snapshot in time is considered, cannot cover a consecutive and thus implicitly time-differentiated distribution. Second, in the definition, "interlinked stages" are considered "from natural resources to final disposal", which also indicates a time differentiation for a product's life cycle.

The relevance of this ALCA definition, considering a snapshot for a specific point in time, will be limited due to its further non-scientific artificial accounting and non-alignment with the ISO definition, as mentioned above, which is less the case if we speak of a "time window" instead of "point in time". Such considerations could rather be considered as a practical simplification (e.g., due to data only being available for a certain point in time) and not as a conceptual obligation or theoretical type of LCA. In other words, considering a point in time for the complete system can instead arguably be a common modeling assumption, out of practical limitations, for LCA modeling frameworks. Alternatively, it could be found ethically acceptable if regarded as a conceptual rule, especially for a time window. In light of potential infiniteness, such matters have also been discussed in the section concerning a cut-off over time for the product system (Section 3.1.2) in the work of Schaubroeck et al. (2021b).

Overall, we hope to have made the issues clear regarding the definitions by Curran et al. (2005) and Finnveden et al. (2009), and their validity, putting indirectly in question many of their derived arguments, all in particular for ALCA, such as those presented by Finnveden et al. (2022). In the end, these issues underscore the interest in abiding by the UNEP-SETAC (2011a) definitions and evaluating them, as was conducted in our study.

It should be noted that Ekvall (2019) additionally states that CLCA addresses "what is the impact of the product on the global environmental burdens?" and in another point, "A consequential LCA (CLCA) gives an estimate of how the global environmental burdens are affected by the production and use of the product". These statements do not align with either UNEP-SETAC (2011a) definition or that of Finnveden et al. (2009). CLCA focuses on the effect of a decision related to a product (e.g., demand for a product or purchase) but not on the impact of the "product". It is vague what this impact would entail, nor what are certain of its stages in a fixed manner. Hence, we have chosen to ignore these statements in the evaluation of the study by Ekvall (2019). Finally, the study by Ekvall et al. (2004) considers not only another definition for ALCA but also two contradictory definitions for CLCA: (1) where a full life cycle and change in it would be considered and (2) the effect of the decision, of which the former is not in line with the UNEP-SETAC (2011a) report definition and the latter is. This all should be kept in mind when comparing our evaluation with his study.

2. Selecting criteria that cover aspects of societal demand

A first distinction needs to be made between what society ideally wants (from an ideological perspective) and what it needs nowadays (from a pragmatic perspective). The former aligns with the evaluation of the value of the concept of the method, and the latter with the evaluation of the value and ease of application of currently available modeling frameworks (and databases) of the method. What the notions of concept and modeling framework entail, particularly in this context, is specified in the study by Schaubroeck et al. (2021b).

It should be remembered that fulfilling the considered criteria is also not necessarily absolute, i.e., criteria can be met to a certain extent. We should also note that a criteria-based approach was also used by Ekvall et al. (2004). An axiomatic approach has been used in other studies (Heijungs, 1998; Schrijvers, 2017; Schrijvers and Sonnemann, 2018), but it does not permit this flexibility and is therefore not used in this context.

2.1. Ideological criteria

From an ideological viewpoint, a core concept behind LCA is, in fact, sustainability, since LCA covers environmental sustainability, or rather the environmental pillar of sustainability, as particularly presented in the context of life cycle sustainability assessment (UNEP-SETAC, 2011b; Valdivia et al., 2021). Different interpretations of what "sustainability" entails exist. For example, Heijungs et al. (2010) defined sustainability as "A thing is sustainable when it can be maintained in a specific state for an indefinite (or very long) time", which in fact, relates more to the concept of durability. The main representative interpretation of sustainability is related to the definition of sustainable development: "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The latter is often regarded as most relevant since it is brought forward by the United Nations, which is a representative institute for the global society (Jørgensen et al., 2013; Schaubroeck and Rugani, 2017).

Nevertheless, regardless of any interpretation, consideration of consequential effects always appears crucial when characterizing something as sustainable to a certain extent, as it deals with the actual deviation of a state or realistic quantification of a system over time. No mention is made of artificial accounting. Moreover, particularly regarding the definition of WCED (1987) cited above, we can conclude that it concerns the relative present and future generations, which implies that it concerns consequential forward-looking effects, not relative past ones or just current effects. This realistic modeling of consequential effects over time in the context of the associated sustainability concept is the **first evaluation criterion**.

Despite an approach being in line with a notion of a concept such as sustainability, if relevance for society is to be evaluated, ethics should be regarded. In this context the question of concern is whether the method aligns with global ethical viewpoints. According to the Cambridge English online dictionary, ethical is "relating to beliefs of what is morally wrong or right" and morally is defined as "based on principles that you or people in general consider to be right, honest, or acceptable". Ekvall (2000) first considered this criterion in the context of ALCA vs. CLCA. The main issue is that different types of ethics are followed in contemporary times. We further specify these types in Section 3.2.1. Within this context of ALCA vs. CLCA, we do not consider ethics concerning the finality of the results, e.g., whether one should only consider the impact on human wellbeing as the finality in sustainability assessment, as studied by Schaubroeck and Rugani (2017). We instead evaluated to what extent ethics are part of the methodology, e.g., product system specification, and to what extent these are accepted by and representative of current societal viewpoints. After all, the distinction between attributional and consequential LCA does not relate to finality as such but rather to the system specification/propagation.

Closely related to the concept of ethics is the concept of "responsibility". It has been a matter of debate in recent articles on attributional vs. consequential LCA (Weidema et al., 2018, 2019; Brander et al., 2019). However, it should be regarded from a broad perspective (not only consequential ethics) and not just as "corporate social responsibility", which Weidema et al. (2019) did, since it is a broader concept, as Brander et al. (2019) mentioned, and not only corporate entities are stakeholders of human/industrial systems. This all relates to the pertinent concept of decision support from an ideological perspective, which has been brought forward in a plethora studies on this topic. More precisely, many works have focused only on the decision support criterion as a crucial point in comparing ALCA and CLCA (Frischknecht et al., 2017; Yang, 2019), despite the importance of the other criteria. To conclude, the **second criterion** is whether the method is in line with certain ethics, related responsibility accounting, and ideological possibilities for decision support.

2.2. Pragmatic criteria

From a pragmatic viewpoint, society desires methods to provide concrete and adequate estimations of environmental impact and sustainability, regardless of ideological criteria. This pragmatic evaluation relates considerably to contemporary aspects such as the availability and quality of existing modeling frameworks and tailored data and databases. An important aspect is that LCA execution should also be conducted while maintaining consistency in practice. Thus, a **third criterion** of relative ease of adequate execution was selected.

Despite the coverage of ideological value, the value in practice might be different, considering the aspect of approximation. For example, it might be better to provide concrete decision support with available outcomes, whereas postponement of a decision implies important risks, following the precautionary principle. Hence, a **fourth criterion** covers the practical value, with a focus on the practical decision support context.

Finally, as a **fifth criterion**, the approach or method should align with regulations or standards, e.g., those implemented for environmental product declarations. This is of value when standards are expected to be followed.

It should be again noted that the evaluation of these pragmatic criteria is considerably contemporary and not absolute, which also implies that this evaluation might and almost certainly will alter in the future.

TABLE 1 Our criteria and those of Ekvall et al. (2004) are compared.

Our new criteria	Explicit criteria by Ekvall et al. (2004)	Comment
Ideological viewpoint	Primary criterion: "extent of contribution to an overall reduction in environmental impact"	/
1. Covering realistic consequential effects over time (environmental impact or sustainability)	"Accuracy and precision of results", mainly referring to accuracy	Quite similarly, although it is practically impossible to check total accuracy, evaluation at a subsystem or sublevel could be possible
2. Alignment with certain ethics and related responsibility accounting	/	This is, to a minor extent, covered in the criterion by Ekvall et al. (2004) on "from knowledge to action" concerning fairness
Pragmatic viewpoint		
3. Relative ease of executing the approach	"Frequency and number of studies", referring to feasibility and the ease of execution, also cover the aspect of "precision" of the above criteria	Very similar
4. Practical value, with a focus on decision support	Primary criterion: "extent of contribution to an overall reduction in environmental impact"	Similar, but we distinguish this from the theoretical finality
5. Consideration in standards (e.g., EPD)	/	
/	"From information to knowledge", implying easily transferred and graspable	This is considerably dependent on the stakeholders involved in grasping the results
/	"From knowledge to action", considering the aspects of perception and doubt	This is considerably dependent on the capabilities of stakeholders.
/	"Resistance to misuse" by a practitioner; vagueness and possibility for methodological choices pave the way for intended biased results	This is considerably dependent on the capability and intention of the stakeholders involved; it is particularly difficult to evaluate this because of the large extent of methodological choices

The alignment of our criteria and those of Ekvall et al. (2004) is not exactly one-on-one, as some of their criteria are a mix of ours.

2.3. Comparison with the criteria of another key evaluation study

Ekvall et al. (2004) not only briefly characterized, albeit in a somewhat different manner, the definitions argued by Schaubroeck et al. (2021b), but also generally evaluated attributional and consequential LCA, the latter being the focus of our article. Their evaluation was again brought forward similarly by Tomas Ekvall alone (Ekvall, 2019), with slightly different definitions of ALCA and CLCA. While these differences in definitions complicate matters (see Section 1.1), we can regard the criteria used in their studies and take considerable stock of their conclusions with these different definitions in mind.

Coming back to the actual analysis of their criteria (Ekvall et al., 2004), these are interesting but rather solely focus on the decision-making process that would support the primary criterion that they bring forward, namely the "extent to which the methodology can be expected to contribute to reducing the environmental impact of human activity in the real world". This primary criterion goes beyond merely the assessment itself and its execution, which we focus on, and also covers the actual further expected effect of communicated results afterwards. Some resemblance between ours and their criteria is presented in Table 1. However, it remains practically impossible to assess the overall complete effect (of reducing the environmental impact) due to the inability to validate it, as Ekvall et al. (2004) also pointed out themselves, similar to how difficult it is to completely validate an LCA (Ciroth and Becker, 2006), or any sustainability assessment for that matter (Schaubroeck T. et al., 2020). The latter authors pointed out that we can and should still check partial accuracy at sublevels such as factories or processes in the context of LCA. Hence, there is still considerable possible validity in the criterion of the accuracy of Ekvall et al. (2004).

This focus on the effect in the studies by Ekvall (Ekvall et al., 2004; Ekvall, 2019) is also challenging, as a method can be applied wrongly by the practitioner or misinterpreted and still lead to a reduction effect in practice. One should note that this relates to the interpretation by externals and is different from the interpretation phase by the LCA practitioner, which is part of the LCA methodology. One can also cross the street blindfolded (bad practice) and not get hit by a car (positive effect). Should we anticipate the misinterpretation of results and apply the wrong methodology, which will adversely lead to an expected and desired positive effect (reduction in environmental impact) because of the foreseen misinterpretation? Ekvall et al. (2004) mentioned that "ALCA may point out the right direction, more often than not", which underscores the plausibility of getting the correct results despite not applying a consequential method. Furthermore, the decision process is highly influenced by external factors, such as the competences of the decision-maker, which make it less objective. In addition, it will also depend on other aspects of LCA that are not covered by attributional vs. consequential analysis, e.g., the specific impact methods that are used.

However, their evaluation approach would be more relevant in cases where actual actors, such as decision-makers, are involved in a participatory approach and/or inquired about, with their behavior

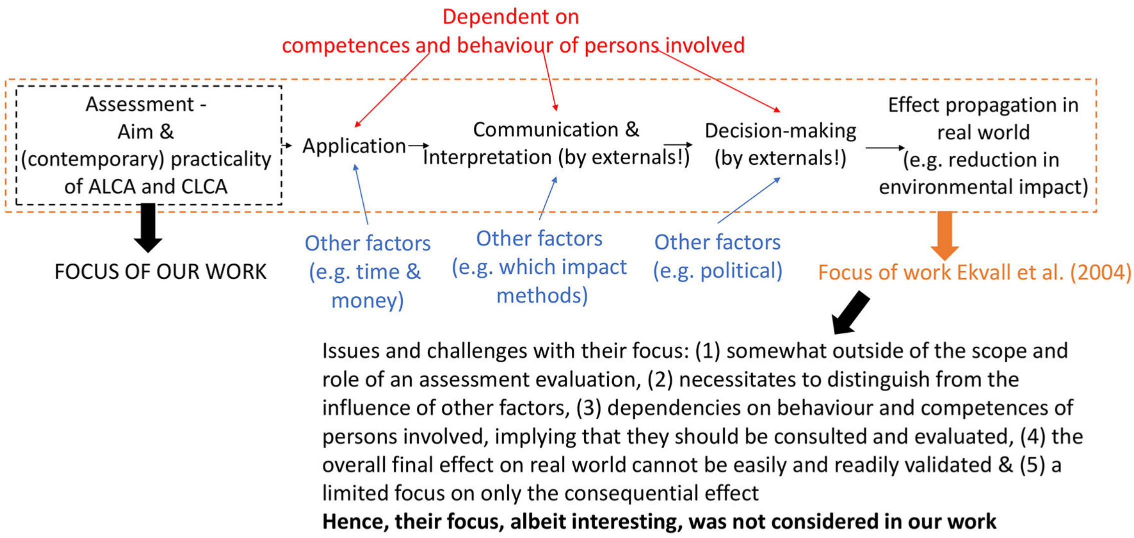

FIGURE 1
The focus of our study compared to that of Ekvall et al. (2004) and that of Ekvall (2019) by extension. We argue why our focus is considered and not theirs.

or thinking analyzed in the evaluation, which they did not do. For our set of criteria, we focus on aspects of the assessment that are mainly objectively defined and do not aim to cover the subsequent effect afterward, which is difficult to consider as it entails the processes described above and depicted in Figure 1. We are not claiming that the focus of Ekvall et al. (2004) is not an interesting one, but rather that it necessitates much more consideration of other factors and behavioral sciences to be of breakthrough quality.

Furthermore, the evaluation by Ekvall et al. (2004) and Ekvall (2019) seem to mainly relate to a single ethical viewpoint: that of consequential thinking. However, other viewpoints might be of interest (see Section 3.2). They only briefly touch upon other viewpoints near the end of their study. Ekvall has innovatively and elaborately considered different ethical viewpoints in his other studies (Ekvall, 2000; Ekvall et al., 2005), creating a breakthrough insight in valuing ALCA and CLCA, making us wonder why this has not been given ample attention in his evaluation studies.

Finally, there seems to be a considerable mix of theoretical and practical aspects in the evaluation of ALCA and CLCA in their studies (Ekvall et al., 2004; Ekvall, 2019). For example, regarding comprehensibility, Ekvall (2019) pointed out: "The basic concept in a CLCA is "consequences." This is also intuitively easy to understand. However, other concepts required to understand the study (marginal production, partial equilibrium, etc.) are more difficult to grasp". It would be better to split that in understanding the concept, on the one hand, and the modeling, on the other hand. One does not need to be aware of all the modeling aspects and terminology when understanding a concept and making a decision based on it. For example, many of us do not understand all aspects of climate change forecasting models, but we are still basing policy decisions on them because we understand the concept of climate change.

To conclude, our focus and criteria are, to a certain degree, different due to a somewhat different focus.

2.4. Contradictions among criteria

Our five criteria are essential to the societal demand for information on environmental and sustainability impacts. These criteria will be used to evaluate attributional and consequential LCA. We can already deduce that these criteria have contradictions, which Ekvall et al. (2004) also pointed out for their criteria. The societal demand, as a whole, is quite complex, and separate criteria can be contradictory. For example, it is impossible to have completely accurate, realistic modeling of consequential effects (criterion 1) due to practical limitations and the desire to obtain concrete outcomes (criterion 3). There are more contradictions, but we will not discuss them all here.

3. Which approach covers what aspects of societal demand?

Based on the above analysis of societal demand, specifying five criteria, we can now better analyse the societal value of attributional or consequential LCA. An overview is presented in Table 4 at the end of this study.

3.1. Criterion 1: realistic modeling of consequential effects over time?

There is a spectrum to fulfilling this criterion, i.e., it is not a yes-or-no evaluation (see Figure 2). Both ALCA and CLCA ideally cover a product system over time, where differentiation over time is needed regarding realistic modeling. However, CLCA aims to be as realistic as possible. Attributional LCA systematically involves only the artificial attribution of a share of the industry's

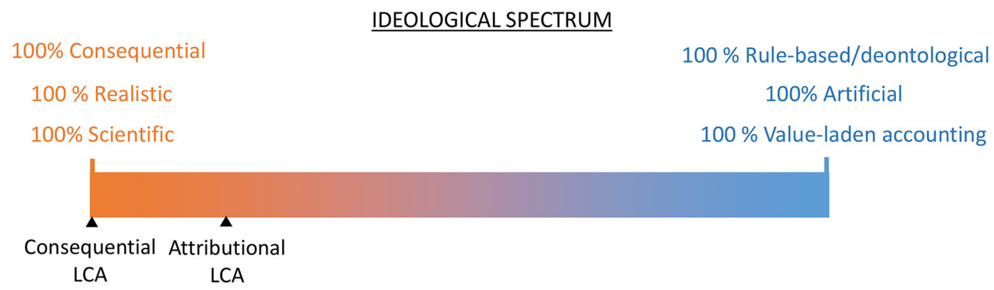

FIGURE 2
Ideological spectrum for life cycle assessment methods and specification of attributional and consequential LCA along this spectrum. Consequential LCA is fully on the left side of the spectrum, whereas for attributional LCA, this is not completely the case as it contains certain rule-based aspects. The exact spot of ALCA along the spectrum is difficult to pinpoint, and in this study and here partially subjectively made.

environmental impact to just a product life cycle and does not cover all types of flows linked with a product life cycle (e.g., information flows). The modeling of the environmental impact of the globe is aimed at being realistic in ALCA. However, the complete specification of the share associated with a product's life cycle is not, as it is restricted by requirements for additivity, implying, for example, the artificial splitting of processes and mathematical restrictions, allowing it not to ideally model systems as accurately as possible.

Moreover, ALCA traces processes and thus impacts in the past, which is not included in the notion of sustainable development, where only the (relative) present and future are considered. Even when considering the product system of ALCA as a snapshot in time, it would be unrealistic and particularly lacking in projecting certain future processes occurring after that snapshot in time. However, it is important to point out that ALCA covers consequential aspects as well, but it is not completely consequential, as CLCA is.

To conclude, CLCA scores better than ALCA on this criterion. This criterion is only regarded from a theoretical viewpoint, not from a practical one (covering whether existing CLCA modeling frameworks are able to model realistic effects accurately?), which is discussed in Sections 3.3 and 3.4. Lastly, the rules in attributional LCA thus also imply a political/subjective influence, which may unfortunately also open the door to malpractices such as lobbying and rent-seeking behavior. Furthermore, CLCA is theoretically free from such influence and retains, ideally, its purely scientific nature. Concerning the latter argument, we regard something as scientific if it can be verified or falsified through empirical results, as emphasized by Popper (2002). Since CLCA propagates plausible, realistic processes with freedom in modeling, this is the case. For ALCA, this is not completely the case. Most strikingly, as already pointed out, partitioning in ALCA implies the artificial splitting of processes with multiple products, which are omnipresent in the real world. Since the artificial process parts do not occur as such, they and their flows cannot be verified or falsified, implying that this partitioning is a non-scientific procedure. For example, one can consider the multifunctional process of cow husbandry, which produces both milk and meat. Partitioning implies that only a part of the cow is considered, together with a part of its flows. This process part cannot be validated or falsified, nor can its flows be measured, as there is not a part of that cow plausibly present in reality. A cow needs to be complete to live and function. Nevertheless, the fact that ALCA is not 100% scientific does not necessarily have to be seen as a weakness but rather as another point of focus, where more caution should be paid to averting negative subjective/political influence and rather having rules that are specified by the overall society and not by mainly a group of experts, which is the case for the ISO standardization process (Schaubroeck, 2022; Schaubroeck et al., 2022). See also Section 3.3.2.

Ekvall et al. (2004) and Ekvall (2019) also point out the more accurate modeling potential of CLCA than ALCA, but this only with regard to having a reduction in environmental impact.

3.2. Criterion 2: ethical alignment of attributional vs. consequential LCA

Recent studies on the debate of the ethical value of attributional vs. consequential LCA (Weidema et al., 2018; Brander et al., 2019) have focused specifically on the ethical characteristics (and related responsibility accreditation) of each method, which were, in fact, already considered in studies by Tomas Ekvall (Ekvall, 2000; Ekvall et al., 2005). The latter studies did not use the exact words "attributional" and "consequential" LCA, which were more clearly introduced later. However, in a conference contribution (Ekvall, 2002), Ekvall used attributional and consequential LCA terminology on the same topic of ethical alignment and relevance, which underscores the likelihood of discussing the same LCA types. His studies were a huge leap forward, and we, in this study, align with them considerably. There are only some points on which we deviate from his study concerning this matter, as discussed below.

3.2.1. Consequential vs. rule-based ethics: specification and relevance

Two prominent ethical viewpoints, specifically within the context of ALCA vs. CLCA, are consequential and rule-based/deontological ethics. Consequentialism bases value and judgement on the induced consequences. A most prominent subtype is that of utilitarianism, which states that the consequences should maximize a certain utility for an action to be morally "better" (Baumane-Vitolina et al., 2016). This utility can be human wellbeing. Returning to consequentialism, this is a universal ethical thinking that is as old as time itself since it follows the linearity of time (as we perceive it) and the causality along it. Even conscient animals are aware of certain consequences of their decisions and actions (e.g., if I don't move fast enough, my predator will catch me) and choose them carefully in the hope of achieving their goals in the future (e.g., survival). If the goal is to obtain a more sustainable world, consequential thinking and propagation are relevant.

The rule-based perspective implies that certain ethical rules must be followed to be ethically "good" (an all-or-nothing approach), regardless of consequences. A plausible exemplary rule is that child labor is not allowed, regardless of what the consequences are for the wellbeing of the child or society. It should also be noted that research in the LCA field has elaborated on child labor's negative and positive effects (Jørgensen et al., 2009). Another prominent set of rules is the Universal Declaration of Human Rights, of which the declaration has been signed by almost all the countries, indicating that consolidated rules can be achieved at a global level despite certain discrepancies in ethical views among cultures and societies. Rule-based/deontological ethics have been prominently characterized by Immanuel Kant (Baumane-Vitolina et al., 2016). These ethics are more complex and not guaranteed universal, but they are upheld and relevant for human society in particular. The extent of relevance depends on the rule and its uptake or acceptance by society. In short, in deontological ethics, rules are used as a framework to approve certain actions.

These two ethical perspectives, consequential and rule-based ethics, are needed but can clash to some extent (Staveren, 2007; Conway and Gawronski, 2013; Baumane-Vitolina et al., 2016; D'Souza and Adams, 2016). For example, should one be involuntarily forced to work, violating a human right, so others can have products to promote their wellbeing (consequential utility maximization)? However, these two ethical perspectives are also intertwined, and attempts have been made to reconcile them, even in general philosophy (King, 2008; D'Souza and Adams, 2016). For example, rule-based ethics may be derived from the bad consequences they cause (killing is not allowed because it ends a person's life). Nevertheless, there is no agreement on a reconciliation. They should, therefore, still be regarded independently. We will thus focus on these two ethical viewpoints separately.

3.2.2. Alignment with consequential and/or rule-based ethics

Following up on criterion 1, in line with consequential effects, the same can be mentioned concerning consequential ethics when evaluating the approaches. More precisely, ALCA and CLCA both cover consequential ethics to some extent, whether or not from an explicit perspective. This finding is different from the study by Ekvall (2000), where ALCA and CLCA are classified as either consequential or deontological.

Yet, CLCA is the only method that covers solely and completely consequential ethics.[3] These consequential ethics are common in everyday life, and CLCA does not provide another interpretation, which implies that it is fully in line with a globally applied and accepted ethical viewpoint. For CLCA, the consequential environmental impact would thus be a consequential ethical evaluation of that decision from an environmental perspective. A decision with a relatively higher consequential environmental impact than an alternative would be a "worse" decision. Ekvall (2000) pointed this out in his study by seemingly claiming that an "effect-oriented" approach (coinciding with CLCA) aligns with teleological ethics (coinciding with consequential ethics).

The normative aspects of ALCA, in general, are in line with rule-based ethics. The norms represent certain rules that are not necessarily based on pure causal or logical thinking and are also subjective. For example, the rule that the product system should cover the complete life cycle. There is also a rule that the sum of the ALCA of all final products should equal the environmental impact of the world. An overview of the rules is presented in Table A2 of the appendix of the study by Schaubroeck et al. (2021b). From an ethical viewpoint, the latter rules could be regarded as certain criteria that should be followed to specify the environmental impact. Just like in society, one would, for example, have to stop at a red light (even if there is no car coming). In the context of ALCA, a product's life cycle environmental impact could be seen as an ethical judgement/evaluation of a product, even if it cannot be changed anymore. Simply put, a product with a higher environmental impact compared to others would be regarded as an ethically more "bad" product and something people would prefer not to be associated with. Ekvall (2000) also seemingly claimed that an "accounting" approach (overlapping with ALCA) aligns with deontological ethics, but he seems to describe the rule that "actions are good to the extent that they support good systems".[4]

Although somewhat out of our scope and relating to the process of communication (see Figure 1), it must be noted that the pure consequential concept behind CLCA makes it more easily graspable in aim (what will be the impact on the environment if I make decision X?) as well as its relevance, in our opinion, than ALCA, where additional rules are at play, making the latter more theoretically complex. We believe that it seems harder to conceptually understand the results of an ALCA and their relevance. Ekvall et al. (2004) confirmed this higher ease of understanding CLCA than ALCA, as they mentioned that "The

3 There is also a rule behind CLCA, namely the rule that it should be consequential starting with a decision, but this might be the only one and reflects the issue of not being able to completely disentangle consequential and rule-based ethics. However, the thinking behind that rule is consequential.

4 Ekvall (2000) and, especially, Ekvall et al. (2005) seem to make a further distinction between the ethical reasons behind the rules, which seems to us to be a complex matter. For now, we can only know that there are rules. Deriving the reasons behind them sometimes necessitates understanding the intentions of the creator of the rules, which we are, unfortunately, not always entirely aware of. Moreover, for teleological (i.e., consequential) rule ethics, one would have to be sure that a consequence is good or bad, which one cannot (e.g., jaywalking may not lead to accidents if there are no cars), except for the basic rule that is about the consequences as such, as defined in the first footnote. As such, we would rather not distinguish between the ethical reasons behind the rules nor specify their difference from "situation ethics", in this study.

concept of consequences is also easy to grasp and relate to. It is probably the intuitive basis for the assessment of most actions" and "The aim of CLCI is clearer than the aim of ALCI. The aim to describe consequences is fairly unambiguous, but the aim to describe a system is vague because a system is that which is subjectively perceived as a system". Despite presenting their and our opinions, which are both considerably biased, in this short paragraph, it might be better to inquire actual stakeholders. Further research with more stakeholders seems thus advised, as yet brought forward in Section 2.3.

Finally, we want to reiterate that ALCA and CLCA focus on ethical differences in system specification/propagation, not finality, as already mentioned in the introduction. However, they can be combined, which is illustrated in Table 2. It should also be note a that a distinction in finality has been debated in the literature, even in the context of LCA. See for example the study by Weidema and Brandão (2015).

3.2.3. Currently limited representativeness and relevance of ALCA rules

Despite the potential ethical relevance of ALCA through its partial alignment with the concept of rule-based ethics, the methodological rules underlying attributional LCA have not been accepted on a global ethical basis. Ekvall (2000) has already mentioned that a broader agreement is needed on what these rules should be, which was presented again by Weidema et al. (2018). The notion that we should be concerned about the environmental impact of a "product life cycle", as defined in attributional LCA, is not universally accepted or widely recognized as a clear and ethically unquestionable matter within society. Why should one care or have to care about, among other things, the environmental impact of the raw material extraction processes that happened in the past (maybe even years ago) to produce a product when buying it now in a supermarket without being able to influence that past extraction process? Should it be a norm or rule that a product's life cycle's impact is relevant? Perhaps only a few top-tier connections are relevant? Weidema (2003) has already expressed the viewpoint that "the concept of 'being associated with' is hardly meaningful beyond a few steps backwards or forwards in the supply chain". Moreover, society as a whole has not agreed upon an environmental impact scheme based on the rule of additivity. These methodological rules could be accepted in terms of standards (see Section 3.5), but this is not the case at the global societal level. Global ethics go beyond practical guidelines and standards with limited representativeness. The UNEP-SETAC (2011a) report, behind the ALCA rules, is not accepted or agreed upon by elected societal representatives but just by a more representative group of researchers. Furthermore, the latter report does not specify which partitioning key to use (see Section 3.6 of the study by Schaubroeck et al., 2021b), even without societal consensus on it. Some standards, such as ISO 14040 or EN15804, have specified partitioning keys and maybe have been developed with consensus among stakeholders from industry and policy, but these are still not representative of acceptance by global society (Schaubroeck, 2022; Schaubroeck et al., 2022).

Similarly, the axioms, i.e., rules, of Heijungs (1997, 1998) for LCA, such as additivity, which now mainly relate to ALCA, have initially not been accepted except by Heijungs himself since he solely authored that study. Heijungs (1998) was aware of this: "The author hopes that the axiomatic approach will be studied and followed by others. If it is possible to find agreement within an authoritative body on the definitions and axioms, it must be possible to derive a method and a large set of properties of LCA". In other words, he is aware that they can be questioned and highlights the need for their acceptance, not absoluteness. Nevertheless, some of his axioms seem to have been translated into rules in the UNEP-SETAC (2011a) guidelines, e.g., the additivity consideration for ALCA. However, as already mentioned, these are not widely accepted in society. Ekvall (2000) already pointed out that an opposite approach could be more interesting (developing a method out of existing rules): "From the viewpoint of rule ethics, the methodological choices depend on what rules are considered to be good. Further research is required to develop an operational procedure to derive LCA methodology from rule ethics".

3.2.4. Evaluation of ethical alignment

To conclude, both ALCA and CLCA are of different but complementary potential ethical relevance, as they align to a certain degree with different types of ethical thinking that stand alone. CLCA follows an ethical viewpoint that has been completely accepted by society in a representative manner, namely consequential ethics. ALCA follows consequential ethics to some extent, but its additional rules are related to deontological ethics. However, the respective rules have not been accepted by society. According to this criterion, only CLCA is of complete ethical relevance nowadays. However, if ALCA rules were globally accepted, this would be different. It should be noted that deontological and consequential ethics are not entirely unifiable. In this regard, as Yang (2019) proposed, a unified LCA framework is thus not directly achievable and may never be.

3.2.5. Responsibility

In this study, responsibility is considered the way it is broadly defined in Online Oxford Dictionaries: "the state or fact of having a duty to deal with something or of having control over someone" and "the state or fact of being accountable or to blame for something" (English by Oxford Dictionaries, 2019).[5] Indeed, in some parts of these definitions, there is a notion of considering consequential effects, which are, to some extent, covered by ALCA and CLCA, as discussed above. Nevertheless, the notion of responsibility, related to ethical alignment, goes beyond a limited interpretation of "corporate social responsibility" that only covers consequential effects in line with consequential ethics, as too narrowly considered by Weidema et al. (2019). In line with "being accountable for something", as mentioned in the above Oxford dictionary definition, one could likewise derive an interpretation of responsibility for a certain role (Brander et al., 2019) or involvement based on rule-based ethics, regardless of

5 It should be noted that responsibility relates to the concept of guilt and "being associated with".

TABLE 2 The difference in ethics in finality and system propagation/specification and their combination, in the case of rule-based and consequential ethics for this study's context.

Ethics in the object or system specification/propagation	Ethics in finality	
	Consequential/utilitarian (e.g., what is the impact on human health expressed in DALY)	**Rule-based (e.g., do not cross planetary boundaries or do not allow child labor)**
Rule-based (e.g., attributional LCA contains some rules)	How much impact is associated with a rule-based system?	Is this rule-based system associated with the breaking of a rule?
	For example: *How much impact (e.g., on human health in DALY) is associated with a product's life cycle? (considering, e.g., the rules for defining the product life cycle and the additivity rule)*	*For example:* *Is this product life cycle associated with the crossing of a planetary boundary share? (considering the rules for defining the product life cycle and the additivity rule)*
Consequential (e.g., Consequential LCA)	How much impact will be caused by a certain action/decision?	Will this action/decision cause a transgression of a rule?
	For example: *How much sustainability impact (e.g., on human health in DALY) will be caused by a product-related decision?*	*For example:* *Will this product-related decision lead to the crossing of a planetary boundary share?*

DALY, disability-adjusted life years.

the consequences. Brander (2019) also underscores the need for both attributional and consequential methods when managing responsibility. Ekvall et al. (2004) mentioned, "Results from a CLCI can be perceived as irrelevant in cases where actions are based on grounds other than their foreseeable consequences. Actions may be guided by a sense of responsibility beyond the foreseeable consequences (Ekvall, 2002)". The claim of Weidema et al. (2018) that "all responsibility paradigms ultimately imply a consequential perspective" is thus not valid. Nevertheless, the latter authors presumed that they should not only focus on "consequential" responsibility (even though they doubt that it needs to be involved in any responsibility paradigm) but also appropriately highlight "value chain" and "supply chain" responsibility, reflecting the responsibility for the impact of the chain of value-adding or supply linked with the product life cycle, related to ALCA.

However, it is not specified or agreed upon what the extent of the role or any kind of responsibility is, similar to the lack of acceptance of the rules behind ALCA (see Section 3.2.3). Brander et al. (2019) claimed that "an agent in question is responsible for, e.g., 'All the impacts associated with the processes used in the physical supply chain"'. However, society has not yet accepted this rule and its extent of responsibility. This shows that a main hurdle with any type of responsibility is the specification of its extent per involved stakeholder. Nevertheless, Weidema et al. (2018) "argue that several actors can assume full responsibility so that responsibility is not a conserved quantity like mass", which we agree with. A producer produces based on existing demand. They can only decide between a limited number of alternatives, e.g., choosing between producing chickens in cages or adopting alternative methods. Moreover, it can be questioned whether the environmental impact, such as the complete production of chicken, should be solely attributed to the producer or the product. Furthermore, since you can only consume what is supplied, all responsibility cannot lie with the consumer. As a solution to this issue, Weidema et al. (2018) pointed out the "sphere of influence", which relates to the extent of influence a stakeholder has (e.g., only choosing between production in a cage or not). This sphere of influence should then be defined per stakeholder and case study, and only different options within the sphere of influence should be analyzed. When considering knowledge, a certain stakeholder might not be aware of alternatives (e.g., another production technology). In this sense, it might be better to expand this concept of "sphere of influence" to the "sphere of knowledge and influence" in the context of responsibility accounting. This is in line with drawing system boundaries due to limited knowledge (Baustert et al., 2017). Finally, in the context of ALCA, one also needs to be aware of the life cycle environmental impact of products, implying a knowledge-driven aspect. This aspect of knowledge also relates to that of the respective supply chain, linked with the difference between using actual versus consequential suppliers (see Section 3.7 in the study by Schaubroeck et al., 2021b). For example, if someone uses an electric car with the knowledge that it will be operated with renewable electricity, the "supply chain" responsibility implies consideration of the supply of renewable electricity. If a person buys the car without that knowledge and presumes that he will be using the current market mix, one should consider the market electricity supply mix for the usage of the car from a supply chain responsibility perspective. This all relates to a final critique of Brander et al. (2019) regarding consequential ethics, namely that a number of decisions are possible. However, in practice, the considered decisions are limited by the scope of the study (e.g., the decision to buy or not buy a car).

Moreover, there is also a "sphere of knowledge and influence", as noted above, in which decisions should be regarded. However, Brander et al. (2019) said that "being unaware of all the possible options does not limit responsibility", which is underscored by Brander alone in a further reply (Brander, 2019). The latter would imply that people need to be all-knowing about possible decisions and their consequences. Would one hold a company responsible for not using ingredient A if the company was unaware that ingredient A existed? This seems highly ethically questionable. However, assessing the extent of stakeholders' knowledge becomes quite complex. Perhaps, any decision-maker should be aware of some straightforward alternatives, implying that the company also has

TABLE 3 Aspects of decision support that are covered by the life cycle assessment (LCA) types (consequential, attributional, and organizational attributional), illustrated with an example of a product purchase decision.

		Consequential LCA	Attributional LCA	Organizational attributional LCA
Quantification objective	**General** (What are the environmental impacts associated with the decision?)	What will be the environmental consequences of the decision?	What is the life cycle environmental impact associated with the products that are of concern for the decision?	What is the life cycle environmental impact associated with the companies of the products that are of concern for the decision?
	Product purchase decision by an individual—example (What are the environmental impacts associated with the decision to buy this product (or another)?)	What will be the impact on the environment if I buy this product and not another?	What is the environmental impact of the product (and another) over its life cycle that I want to buy?	What is the life cycle environmental impact of the companies behind the product (or another) that I want to buy?
Ethical implication (in the context of a decision)	**General** (Given the associated environmental impact, should this decision be made or not?)	Should this consequential environmental impact occur or not? Should this decision be made, given its consequential environmental impact?	Is this product's life cycle environmental impact approvable/acceptable (even if a part happened in the past or cannot be influenced by the decision)? Do I approve/accept this impact?	Is this life cycle impact from the companies approvable/acceptable (even if a part happened in the past or it cannot influence it)? Do I approve/accept this impact?
	Product purchase decision by an individual—example (Should I buy this product (or another)? Do I want to be associated with these impacts?)	Should I cause a consequential environmental impact by buying this product (or another)?	Do I approve of the life cycle environmental impact of the product (or another) I want to purchase?	Do I approve of the life cycle environmental impact of the companies behind the product (or another) I want to purchase?
Potential responsibility implication for decision-maker	**General** (what potential responsibility do I bear regarding environmental impact if I make this decision?)	Do I want to bear the potential responsibility for the consequential environmental impact caused by my decision?	Do I want to be held potentially co-responsible for the life cycle environmental impact of the decision, together with the other stakeholders for the life cycle?	Do I want to be potentially co-responsible for the life cycle environmental impact of the companies related to the decision, together with the other stakeholders in its life cycle chains?
	Product purchase decision by an individual-example, what potential responsibility do I bear regarding environmental impact if I buy this product?	Do I want to bear the potential responsibility for the consequential environmental impact caused by purchasing this product (or another)?	Do I want to be potentially co-responsible for the life cycle environmental impact of the product (or another) I buy? Do I want to share this responsibility with the other stakeholders in the life cycle?	Do I want to be potentially co-responsible for the life cycle environmental impact of the companies behind the product (or another) I want to purchase, together with the other stakeholders in its life cycle chains?

These LCA types aim to address certain quantification objectives that relate to decisional/ethical implications and bearing responsibility, whereas for ALCA, this is under the presumption that a product's life cycle environmental impact is of ethical relevance (i.e., the rules behind ALCA have been widely accepted by society). This all showcases the potential complementary nature of how these types can support a decision. For responsibility implications, we consider that the decision-maker is aware of the estimated environmental impacts.

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to be knowledgeable to a certain degree. This is, however, leading us into a complex ethical discussion on the actual responsibility of stakeholders. We preliminarily conclude that responsibility can be related to different ethical viewpoints. For a responsibility characterization, the total group as stakeholders could first be regarded as responsible for the complete product system, implying a co-sharing of responsibility in ALCA. For separate stakeholders and their decisions, a sphere of knowledge and influence should be advisably regarded. See Table 3 for an overview.

However, such an evaluation of the actual full responsibility of stakeholders, also implying the evaluation of their knowledge and influence (as explained above), goes somewhat beyond the scope of an assessment such as LCA. LCA evaluates and assigns responsibility primarily to entities, namely alternative product life cycles or decisions, and not primarily to stakeholders, with the latter only implying a potential responsibility assignment. The latter means that LCA studies could only partially support a stakeholder's ethical judgement or evaluation, serving as a source of information but not fully serving that purpose. This distinction is made clear in the Figure 3 below.

3.2.6. Decision support

A related notion is that of theoretical eligibility for decision support, linked with ethical alignment and responsibility. When examining the literature, we find that many studies only focus on the decision support criterion as a crucial point for evaluating LCA (Frischknecht et al., 2017; Yang, 2019). The latter authors seem to agree that a decision should be evaluated by the consequences it causes, and therefore, CLCA is the right method. From this consequential perspective, for a decision, the effect of a changing system and global impact should be considered, which is not the case for ALCA, as it focuses on attributing a share of the impact of a fixed or predefined world and global impact (see Table 3). A recent inquiry by Weidema et al. (2020) also made clear that there is prominent interest in CLCA. However, other experts have raised some interesting reflections on that matter. Brander (2016) claimed that "attributional LCA can be used for making other kinds of decisions, related to assigning responsibility, etc., that are not mitigation actions in themselves, i.e., they do not directly reduce environmental impacts." Brandão et al. (2017) stated that, "For people arguing that different normative standpoints and/or decision criteria should be considered, other modeling approaches and tools can also be of interest to use instead of CLCA or as a complement to CLCA. This also suggests that ALCA and CLCA may complement each other and be useful for groups of decision-makers with mixed or unarticulated opinions about the most appropriate basis for decisions". Ekvall (2002) wrote that "the results from a consequential LCA can sometimes seem unfair, and we do, in some cases, base our decisions on a sense of responsibility that goes beyond the consequences of our actions". This all points to other aspects of supporting a decision besides a consequential viewpoint. Taking stock of the above reflection on ethics and responsibility, it becomes clear that making a decision has links to consequential ethics through the consequences it generates, ascertaining the role of CLCA in that regard. However, it also becomes clear that making a decision implies involvement in a product system of concern, and thus, one could be considered to be approving of and sharing co-responsibility for its environmental impact based on the rules that define that product system and its impact. For ALCA, this product system would be the life cycle of the product of concern for the decision, as restricted by the ALCA rules. See Table 3 for an overview. One should also note that this is under the presumption that the rules of ALCA would be accepted (See Section 3.2.3), i.e., one can use the environmental impact of the life cycle of a product as a means to judge. In Table 3, we also innovatively point out the role that organizational LCA (Martínez-Blanco et al., 2015), the attributional version, could play. We should also note that a specification of organizational consequential LCA could be done but is theoretically not needed, as a decision in general is already covered in CLCA, including the ones taken by organizations, and consequential effects will also ideally cover effects on organizations and their impact.

See Figure 4 for a specific concrete consumer decision dilemma and how attributional and consequential LCA may provide different perspectives. Overall, there is potential for valuable complementarity in ethical alignment, responsibility appointing, and decision support between ALCA and CLCA.

As a final remark, Ekvall (2000) seems to criticize the idea that CLCA in decision support may lead to the establishment of sub-optimized systems with regard to environmental impact. For example, he points out that in the case of a country that produces renewable energy with the excess being exported and fossil-fuel-based energy being imported with an increase in demand, CLCA would stimulate the country to cut off electricity and use its own excess better, as then the impact score would be lower. Nevertheless, this is a flawed viewpoint since it considers matters from a limited stakeholder viewpoint (in this case, a country). In contrast, CLCA does not have this restriction (effects of how external countries would deal with the loss in an inflow of electricity should be considered) and ignores the fact that one could also evaluate the consequential effect of installing renewable energy plants in the past retrospectively. These also seem to be issued in the modeling application, which is a further step and depends on the modeling quality and capabilities. Weidema (2003) also counters this specific criticism of Ekvall (2000).

3.3. Criterion 3: relative ease of adequate execution

From a pragmatic viewpoint, covering the **third** criterion of relative ease of executing adequately, attributional LCA may be and has often been regarded as easier to apply, but this can be challenged (Brandão et al., 2017). Many aspects come into play, and they are briefly touched upon separately in the below subsections, although they also somewhat overlap.

3.3.1. Modeling and its complexity

The complexity of cause-effect modeling may be particularly perceived as an extra difficulty for CLCA compared to ALCA at first sight. Covering complex consequential effects can be achieved by coupling with other types of models, which can make it quite

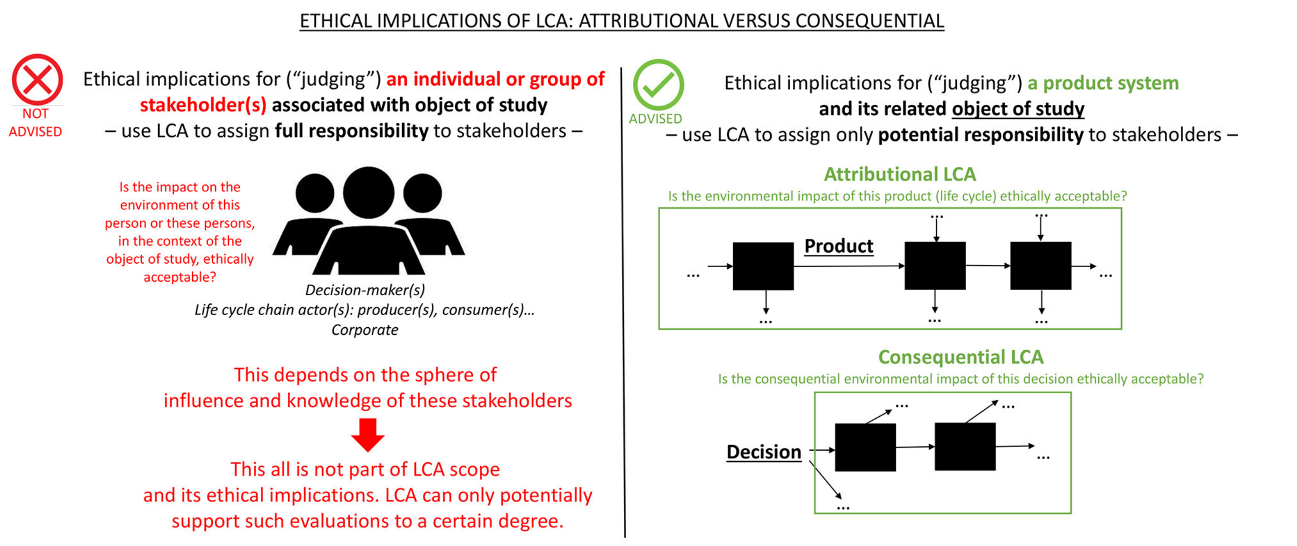

FIGURE 3
Ethical implications of LCA, with a focus on attributional vs. consequential LCA.

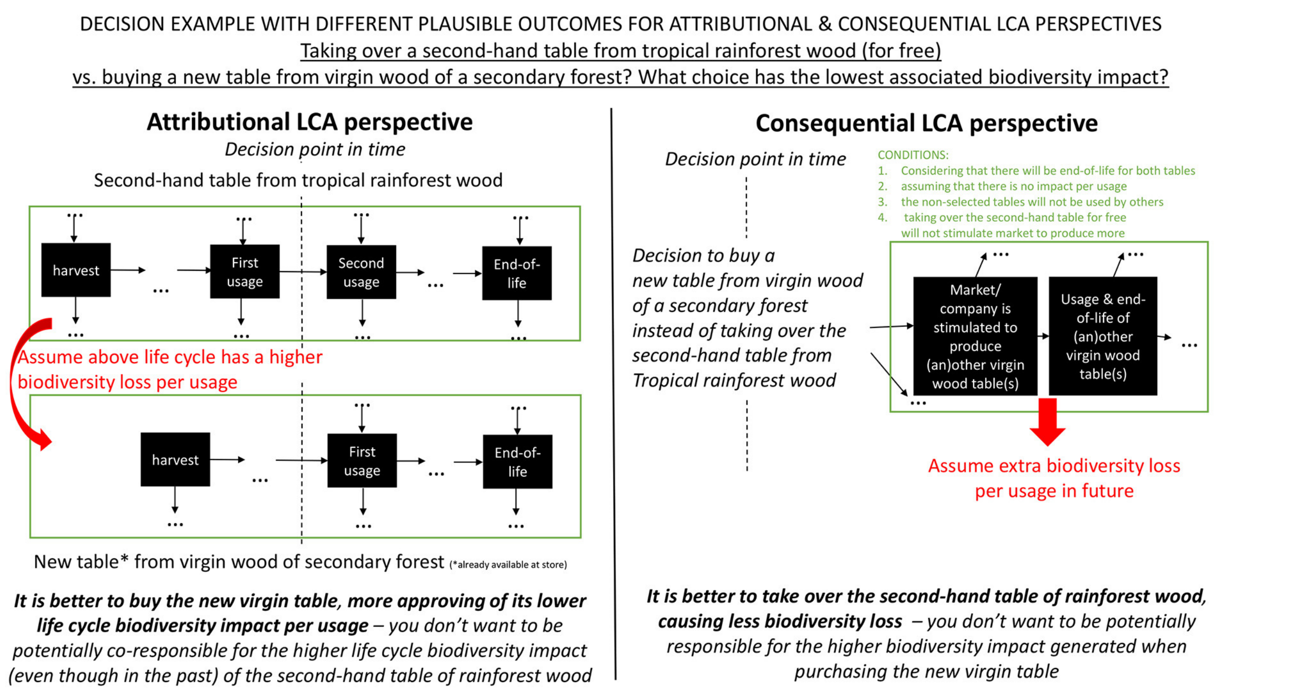

FIGURE 4
A concrete example of a decision where attributional and consequential LCA perspectives lead to different plausible outcomes.

a complex endeavor (Ekvall et al., 2004). To delimit complexity, constrained modeling frameworks have been developed under certain assumptions. The most prominent one is the "substitution, consequential, and long-term" modeling framework consolidated by Weidema et al. (2013) for small-scale decisions, in which, among other factors, co-product effects are limited to substitution effects associated with a demand-constrained market, linearity is presumed, and effects over the long term are considered. The latter framework also focuses on one type of decision: extra demand for a product on the market. A main issue is the vagueness of this type of decision, as products are often not "demanded". They are more commonly purchased, used, ordered, or replaced. Decisions relate to the latter specific actions and their conditions. In practice, the "extra demand of a product" is commonly presumed to be induced by a purchase or usage decision. Tailored frameworks should be developed per type of decision; for example, this was performed by Schaubroeck S. et al. (2020) for the replacement decision. With regard to other and more complex modeling of background aspects, e.g., the effect of price change, we refer to the review of Palazzo et al. (2020).

However, the fact that CLCA is more complex in its modeling is a major misconception. Attributional LCA also needs to cover complex modeling. In ALCA, the state of the world over time and across the product system is also not constant or unknown and needs to be modeled, where complex mechanisms should be covered to specify interlinked processes, albeit not in a disruptive manner related to the object of study. This is illustrated in the use of complex Integrated Assessment Models (IAMs) to model background processes in studies with a primarily attributional scope or modeling (Beltran et al., 2020; Baustert et al., 2022). Even when studying the past, certain estimations of states need to be made, as not everything is recorded in the past. For process specifications, similar effects as those specific to consequential LCA must thus be modeled, e.g., price changes, population growth, co-product effects, and so on.

Bamber et al. (2020) did not address these effects in their consideration of ALCA. This is despite the latter authors considering another definition of ALCA, namely that "ALCA examines a snapshot of the current or past state of affairs to determine environmental impacts that can be attributed to the product studied, assuming a static system". We should also note that we have criticized this definition in Section 1.1. However, for certain unknown data points, modeling might be needed to obtain them. For example, if the exact electricity mix is unknown at the considered point in time, one can use models for a price change or even machine learning, as exemplified in the following article published in this journal (Portolani et al., 2022). If such modeling is needed in the background, many decisions that have shaped the world may need to be considered. In addition, ALCA can and has also been applied to hypothetical alternative scenarios, e.g., the installation of new technology. In fact, to know the data in that case, consequential modeling should be executed for that decision, and then afterwards, a product's life cycle is defined and its impact computed for that hypothetical scenario. The complete procedure would entail the ALCA modeling, meaning it would include the complexity of the consequential modeling. This latter has been explained by Schaubroeck et al. (2021b).

Ekvall et al. (2004) and Ekvall (2019) also seem to overlook this complexity in modeling ALCA in their evaluation. In many ALCA studies, constant background conditions and process characteristics are implicitly considered or derived, and the only thing that needs to be modeled is the product life cycle among these constant processes and interlinkages, giving the impression of higher simplicity. Nevertheless, even in the foreground, the specification of processes may necessitate complex and dynamic modeling (Schaubroeck, 2022b). Even more so, as already mentioned, if an ALCA is executed for a product in hypothetical scenarios, e.g., with a decision (Schaubroeck et al., 2021b), the effects of a decision would still have to be modeled.

Thus, the complexity will depend on the specificity of the case and the background situation considered, and a CLCA is not guaranteed to be more complex than an ALCA. Furthermore, both models cover complex impact assessment models in the same regard. Both methods may thus also be highly uncertain in their outcomes on the same level.

Finally the raised issue by Ekvall et al. (2004) and Ekvall (2019) of higher difficulty in understanding the modeling outcomes of CLCA compared to ALCA due to higher modeling complexity may thus also be unsubstantiated as existing ALCA studies commonly lack in modeling complexity.

3.3.2. Available databases

A crucial prerequisite for adequate LCA execution is the availability of databases covering hundreds of processes within the product systems, both for ALCA and CLCA. For ALCA, many databases or database versions are available. For environmental CLCA, there is only one process-based one: the consequential system model of ecoinvent 3.x (Weidema et al., 2013; Wernet et al., 2016). It is also restricted to the modeling framework explained in the previous section: "substitution, consequential, and long-term". In the case of environmental Input-output LCA, only a consequential version of EXIOBASE exists where only the substitution effect as a consequential mechanism is considered (Merciai and Schmidt, 2018; Merciai, 2019). In the case of social LCA, the two prominent databases, PSILCA (Maister et al., 2020) and SHDB (Benoit Norris et al., 2019), are based on input-output models with predominantly attributional modeling: EORA and GTAP, respectively. As such, considerable attributional modeling is unavoidable for consequential social LCA if such a database is selected. It is important to remember that this database screening is limited to the best of our knowledge.

3.3.3. Consistency

Conducting an LCA should be regarded while maintaining consistency in its application (Weidema, 2019). A main issue with applying ALCA is the lack of a standardized and consistent partitioning key, which is necessary to adhere to the additivity rule. The ecoinvent 3.x database mainly uses an economic partitioning key and exergy as a partitioning key for few processes. The latter choice aligns with the advice to employ a physical partitioning key for processes in which products can be independently varied (ISO, 2006). However, this combined application remains inconsistent in ALCA, where a single consistent partitioning key is needed (Weidema, 2018; Schaubroeck et al., 2021b).[6] To the best of our knowledge, some databases, such as Agrifootprint, are consistent in the partitioning key. Moreover, for the Allocation at the Point of Substitution (APOS) method for ALCA, which is argued to be

6 The ISO 14044 has a general inconsistency with regard to its solutions for multifunctionality, as pointed out by Schaubroeck et al. (2022). More precisely, on the one hand, the ISO advocates for multifunctionality solutions to be in line with the goal, and on the other hand, there is a hierarchy. Aligning with an inconsistent ISO 14044 text on this matter is not possible. In this case, we only align with the need for multifunctionality solutions to be aligned with the goal, as advocated by the latter authors.

fully consistent with the product life cycle definition of ALCA (see Section 3.1.3 in the study by Schaubroeck et al., 2021b), there is only one database available, namely the APOS version of ecoinvent 3.x (Weidema et al., 2013; Wernet et al., 2016). Finally, concerning consistency, a major issue for ALCA is the lack of life cycle impact assessment methods that partition environmental processes and respect the additivity rule (see Section 3.5.1 in the study by Schaubroeck et al., 2021b).

However, the possible inconsistency in data and data quality (e.g., for process X, methane emission amounts are covered, but this is not the case for process Y, even though methane emissions are reported) should also be kept in mind (Plevin et al., 2014) and may be regarded as insurmountable. However, this is application-dependent per case study.

3.3.4. Additivity

An important practical advantage of ALCA would be additivity, i.e., measuring the total environmental impact of a set of functionalities by summing the ALCAs of separate functionalities. It is essential to specify that in this context, additivity is only considered as a pragmatic benefit, not a necessity, not even from an ideological standpoint. Brander et al. (2019) seemed to argue that a lack of additivity in consequential LCA is a crucial drawback, as additivity is needed in light of "science-based target settings", such as planetary boundaries. However, if this splitting of such targets among sectors or industries is performed based on additivity, it is quite artificial since it overlooks the interconnectivity between industries (interlinked cause-effect chains) and thus the improbability of dividing impact across industries (see Section 3.6 of the study by Schaubroeck et al., 2021b). Artificial targets per sector can only be met by artificial systems created through attributional LCA. However, Brander et al. (2019) presumed that such a target setting is always based on an additivity presumption. Alternatively, this "science-based target setting" cannot comply with the need for additivity and set targets without that constraint. If such a "science-based target setting" explicitly states additivity, attributional LCA is appropriate. However, one can then question the validity of the science-based target setting if it intends to cover realistic situations. Overall, target settings can be performed in an attributional or consequential manner, and this is not fixed, implying no theoretical reasoning in favor of additivity. It is crucial to remember that target setting can also be normative with regard to finality, e.g., planetary boundaries, but this does not restrict system propagation to a certain type (see Table 2), e.g., ALCA. Coming back to the pragmatics of additivity, the complexity, as discussed in Section 3.5 of Schaubroeck et al. (2021b), implies that prior to adding ALCA outcomes of different products, it should be checked whether their life cycles do not contain products that are the same and do not together cross the global environmental impact or demand of final products, which is especially relevant when considering large amounts. If they are, this double counting should be avoided. We do not deny that the goal of obtaining an aggregated outcome is relevant, but we do not see a need as to why this aggregation would necessitate additivity. To conclude, additivity remains a pragmatic, useful matter, and additivity as a rule/ideologically is not widely accepted by society (see Section 3.2) or of guaranteed relevance.

3.3.5. Need for rule specification and/or validation in ALCA

A specific need for ALCA due to its rules, which is lacking for CLCA, is the need for specification and/or validation of certain rule aspects. This concerns, in particular, the selection of the partitioning key. On the one hand, specification can be delimited through goal specification, where the partitioning key choice can be unequivocally derived from the predefined goal. For example, Weidema (2014) pointed out the use of revenue partitioning in cases where the goal is "What are the environmental impacts related to the activities that contribute to the cost of the product?". On the other hand, this could also be agreed upon by a representative group. However, given the normative, abstract, and unrealistic nature of rules such as partitioning, which do not aim to reflect reality, this should be validated by society at large or its representatives, not just a group of experts as is the case in the ISO process (Schaubroeck et al., 2022), especially since it may have a dire influence on the outcomes. This has already been brought forward in general in Section 3.2.3. Finally, we should remember that the challenge of rule choices (such as the choice of a partitioning key) in ALCA cannot be overcome through better modeling.

3.3.6. Conclusions for criterion 3

In general, concerning criterion 3, both ALCA and CLCA have their challenges. ALCA may be perceived as more readily applicable due to its additivity and perceived modeling simplicity with lower uncertainty. However, the former may require a check for double counting, and the latter is a misconception, as ALCA should also cover complex modeling with related high uncertainty. If consistency is considered an indispensable requirement, which we believe it is, then-current ALCA applications cannot be adequately executed due to a lack of LCIA methods that partition multi-input environmental processes, but this can be overcome. Moreover, ALCA requires further specification or validation of its rules. However, for CLCA, fewer databases are available, and not all types of decisions have been studied, pointing out a further need for improvement.

3.4. Criterion 4: practical value, in particular for decision support

In theory, ALCA and CLCA have different conceptual aims and potential ideological relevance, as discussed in Sections 3.1 and 3.2. However, in practice, the respective modeling might be used differently. Most notably, even though only CLCA focuses on the consequential effect of decisions, things might be different when applied in practice due to practical limitations, and ALCA modeling could serve in certain ways as an approximation of CLCA. This is what we analyse in this section. Ekvall et al. (2004) and Ekvall (2019) also evaluated this possibility for ALCA outcomes to support decisions, but they also covered further steps that are dependent on the decision-maker's competencies as specified in Section 2.3.

Whether a single ALCA modeling framework can be used to address a consequential LCA question, i.e., model the consequences of a decision, has been theoretically discussed by Schaubroeck et al. (2021b) in Section 3.10 of their study. The first part of Figure 5 presents that approximation option. Overall, one would then implicitly assume that many matters are constant regarding suppliers, impact, processes, and so on. In brief, this approximation is more accurate if history repeats itself. This is more likely the smaller the amount studied. Related to this, on whether to use attributional or consequential information for product choice studied among students by Weidema et al. (2020), a single student claimed that "a low impact reported by the attributional label indicated past good behavior, which was perceived as providing a good indication for the expected future impact", following this paradigm of history repeating itself, whereas the majority of the students favored consequential information.

Moreover, there are also modeling issues with regard to this approximation, notably the unrealistic partitioning of processes (which can have a huge influence on results), and we do not believe that many users and external stakeholders are aware of these or have difficulty grasping them. The lower accuracy of ALCA modeling for consequential studies has also been pointed out by Ekvall et al. (2004) and Ekvall (2019). If one is not aware of these assumptions or issues, one can regard the usage of attributional LCA modeling for consequential LCA as a misinterpretation. However, there can be practical constraints, such as the lack of adequate data or time, that could restrict choice to attributional modeling for CLCA, making it acceptable in practice, but there are consequential LCA databases, so arguments are limited in that regard. Overall, this seems like a low-quality approximation in our opinion, and one is better off with proper CLCA modeling.

ALCA modeling could also be presumably used to approximate the effect of a decision in a comparative way through two ALCAs, one for a scenario with a decision and one without. For example, this could be the improvement or alteration of a process as studied by Baustert et al. (2022), i.e., the ALCA of the product with the conventional process and an ALCA with the altered process. One can then wonder whether this difference would be the same as the result of a CLCA. Baustert et al. (2022) do not have that focus but evaluate them as attributional LCAs or as approximations of CLCA. The second part of Figure 5 touches upon this difference between the two ALCAs and whether it would approximate a CLCA. Since caused effects cannot be directly associated with interlinked processes of the product provision process, this approximation is less likely. For example, if the altered process consumed X kWh more electricity, that could presumably cause X kWh more electricity production using solar panels on the market (a consequential effect), but the actual electricity consumed by the process could still be a future mix where only the share of solar panel electricity has increased slightly compared to the original (difference between attributional LCAs), being not completely out of solar panel electricity. Moreover, the product life cycle studied in attributional LCA also spans the relative past of the product delivery, which could be before the decision. As such, it is not possible to consider this the difference between before and after the decision, but rather without and with the decision, possibly hypothetically. Finally, a difference between two ALCAs before and after a decision still presents a difference in labeled impact caused by that decision, but it is of relevance for a difference in rule-based responsibility. If one goes to the shop and buys product A, because of this purchase, the next time one buys the same product, the attributional impact label may have changed due to the first purchase. As already explained, this is not a change in environmental impact caused by the decision to buy product A, but a difference in impacts associated with the product life cycles. Finally, there are also all the other modeling issues that can cause further complexities in determining the differences in impact. Yet again, in our opinion, considering this approximation as an equality implies a misinterpretation of what ALCA and CLCA entail. Nevertheless, in this case, it could be an approximation under practical constraints, but it seems less accurate than the use of a single attributional LCA (the first option).

3.4.1. Practical uncertainty

A relevant aspect of practical value and decision support is the uncertainty of the outcome, as briefly discussed by Weidema et al. (2020). In this context, it is crucial to take into account the practical infeasibility of covering all uncertainty because of the lack of knowledge (Baustert et al., 2017), the vastness of methodological choices (Kuczenski, 2019), and the impossibility of validating total impact (Ciroth and Becker, 2006). Even though accuracy cannot be validated at a global level, it could be checked at subsystem or process levels (Schaubroeck S. et al., 2020). Although many studies have highlighted the need for quantitative uncertainty assessment, specifically in the context of ALCA and CLCA, which we do not want to undo, its relativism should be regarded, and qualitative aspects should be considered as well (Huppes and Schaubroeck, 2022). Returning to ALCA vs. CLCA, Bamber et al. (2020) have reviewed different sources of uncertainty but, as already mentioned, completely overlook that similar complex modeling is, in fact, ideally needed for ALCA compared to CLCA. Similarly, uncertainty can be high. In particular cases, uncertainty might be slightly higher for CLCA due to its change-oriented focus. However, in the context of realistic modeling and consequential decision support, when splitting uncertainty into accuracy and precision, accuracy is considered more relevant than precision, favoring CLCA (Ekvall et al., 2004; Weidema et al., 2020).

3.5. Criterion 5: being in line with regulations or standards

Whether or not these rules of attributional LCA are ethically accepted (see Section 3.1), within standards and regulations set up by the LCA community or related societies, the rules or restrictions of attributional LCA modeling are often commonly specified in them (Schrijvers et al., 2016). For example, the Environmental Product Declaration, e.g., ISO 14025, is restricted to only versions of databases based on ALCA, more precisely, the cut-off approach (see Section 3.5 in the study by Schaubroeck et al., 2021b). On

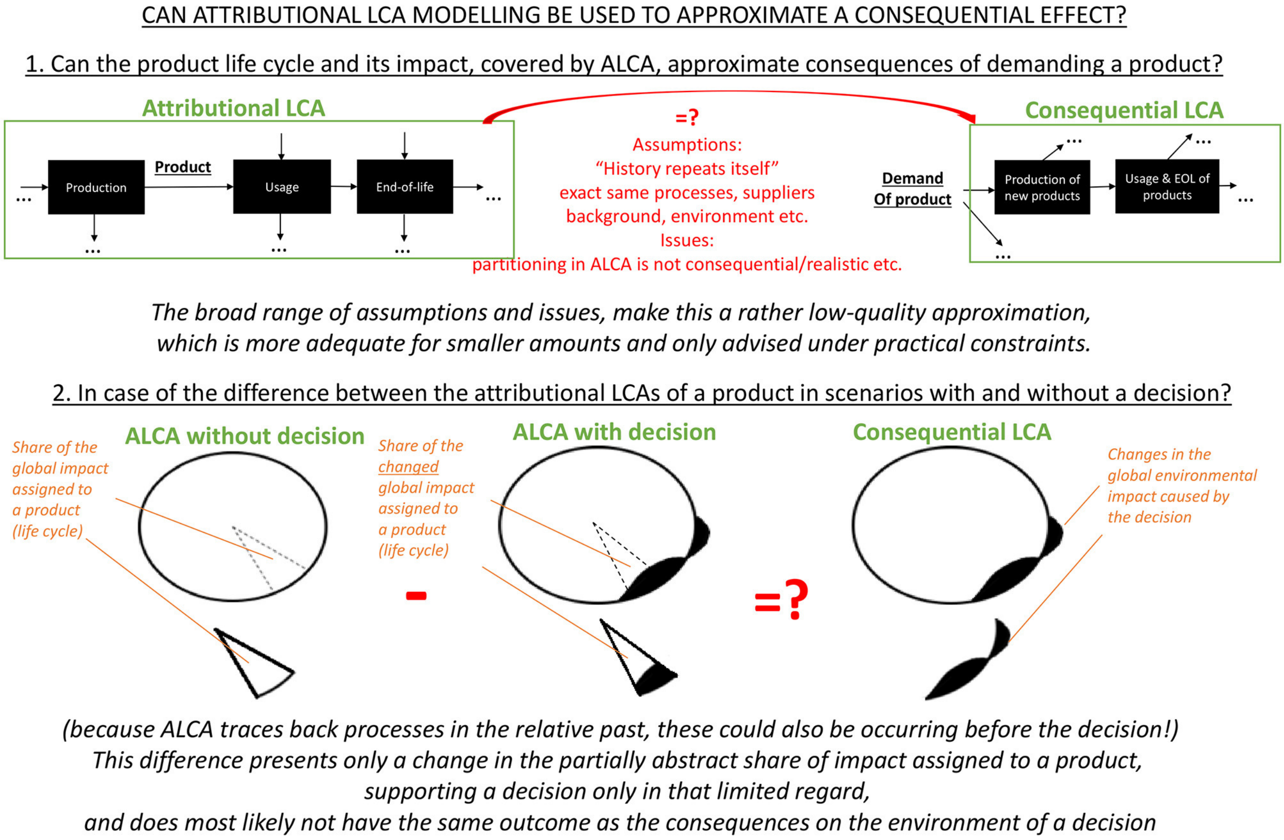

FIGURE 5
Usage of attributional LCA modeling to approximate a consequential effect.

the contrary, within ISO14025, module D covers the benefits of recycling by covering the substitution of alternative products with the same functionality, which is a consequential effect and not part of an attributional LCA. The Product Environmental Footprint (PEF) method has been similarly questioned in its unclear focus and limited modeling approach between attributional and consequential LCA (Ekvall et al., 2021; Schrijvers et al., 2021). Furthermore, even the ISO 14040–14044 standards are unclear in their focus and delimitation to either ALCA or CLCA (Schaubroeck et al., 2022).

To conclude, standards lack mainly consistency and a clear selection of either ALCA or CLCA. Nevertheless, they seem to favor attributional LCA and its overall modeling. Standards are also often used for science-based target evaluation. However, as already mentioned in Section 3.2.1, the specific goal of the science-based target will specify the criteria for the standard, which, in this case, is ALCA or CLCA.

Furthermore, standards may be perceived as providing a fixed way of consistently comparing LCAs, but in reality, there are still methodological choices to be made, and the quality of the data is variable. For example, all standard rules may have been followed, but unrepresentative data are used. Data collection is still not fully standardized as such. Hence, such standards merely facilitate comparability to a certain degree, but they do not ensure it.

Finally, the eligibility and value of the current ISO 14040-14044, which are at the core of many aspects of many other standards, can also be questioned due to many further issues. One can even question the need for standardization beyond fixing nomenclature in the field of LCA (Schaubroeck, 2022). This all makes this criterion less of a concern currently, but if standards are to be kept, CLCA should be distinguished and brought forward more. As an overall ad interim solution, the more open and general LCA framework by Schaubroeck et al. (2022), in which ALCA and CLCA can be separately specified, may be apprehended.

4. Conclusion of the comparison and further outlook

An overview of the evaluation per criterion is presented in Table 4. To conclude this comparison, CLCA is currently the preferred method from an ideological viewpoint. Even though ALCA is, to a certain degree, consequential, it is also based on rules that can be regarded as relevant following deontological ethics, but these have not been accepted as such worldwide. For example, why should a product-related decision, in light of environmental impact, depend on the processes that happened way further upstream and downstream in the product life cycle without necessarily influencing them? Further specification of the research question could help delimit rule specification, e.g., certain partitioning keys can be restricted by the type of goal. This does not mean that ALCA could not be a relevant method, but it is currently not the case since society did not yet accept its rules (looking beyond a select group of experts or

TABLE 4 The evaluation of ALCA and CLCA according to selected criteria for societal demand on sustainability and environmental impact assessment.

	Attributional LCA	Consequential LCA
Ideological viewpoint criterion 1: covering realistic consequential effects over time from a theoretical perspective (environmental impact or sustainability)	Not completely but only to a lesser extent due to rules such as additivity, abstract partitioning, and normative product system	Completely
Ideological viewpoint criterion 2: alignment with certain ethics, related responsibilities in accounting, and decision support	To some extent, in line with consequential ethics, Its methodological rules are deontological but not agreed upon society-wide	Completely in line with consequential ethics
Pragmatic viewpoint criterion 3: ease of adequate execution	Modeling complexity and uncertainty are high. Many databases exist. Additivity makes it easier but requires an equal methodology and a check for double counting. A major issue is the lack of LCIA methods that are in line with the ALCA concept	Modeling complexity and uncertainty are high and may often be slightly higher due to the focus on disruption by a decision. Although a few databases and modeling frameworks exist, they need to be adapted to more decision types
Pragmatic viewpoint criterion 4: practical value	In the case of consequential decision support, it is a lower-quality approximation that should only be selected under practical constraints	In the case of consequential decision support, this is the go-to method.
Pragmatic viewpoint criterion 5: consideration in standards (e.g., EPD)	More considered in standards, but not always exclusively and consistently (e.g., together with CLCA aspects)	Less is considered in standards, although some aspects are.

companies). We should note that almost the same conclusion has been brought forward by Ekvall (2000) but seems to have been questionably overlooked in the LCA community. As an alternative, Ekvall (2000) pointed out an interesting inversed approach, where LCA methodology is derived from rule ethics. These are important venues for further relevance specifications for ALCA.

From a pragmatic perspective, things are different. ALCA cannot be consistently applied because no LCIA method partitions multi-input environmental processes. However, ALCA is still often the main recommended method in standards for science-based targets, with many databases aligned with ALCA. However, only the APOS version of ecoinvent covers a complete product life cycle without cutoff, which is consistent with the actual definition of ALCA. The only readily applicable consistent CLCA at the full database level is based on the "consequential" modeling framework and associated versions of ecoinvent and EXIOBASE. Yet, since they are available, the lack of a CLCA database cannot be used anymore as a constraint to opt for ALCA modeling.

With regard to consequential decision support, CLCA modeling frameworks should be preferred, and ALCA modeling frameworks are low-quality approximations that should be avoided if practically possible. Finally, modeling complexity and uncertainty (concerning precision) are at a very similar level for ALCA and CLCA, as both cover projections of background economic systems, undoing the misconception that this would be considerably more of an issue for CLCA.

Overall, CLCA should be more widely applied than ALCA. More CLCA databases should be created and decision types studied. CLCA standards could be developed, and science-based targets can also cover consequential matters. However, as a final take-home message, the safe bet for the practitioner is to apply both ALCA and CLCA if resources allow it, but priority should still be given to CLCA if resources are limited.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1063583/full#supplementary-material

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