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Beyond boundaries: Comparative perspectives on attributional and consequential life cycle assessment

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Abstract

Life cycle assessment (LCA) is widely regarded as the most comprehensive methodology for evaluating the environmental impacts of products and systems. Two principal modeling approaches have emerged within the LCA discipline: attributional LCA (ALCA) and consequential LCA (CLCA). While ALCA aims to describe the environmental burden associated with the production and use of a product under existing conditions, CLCA seeks to capture the system-wide environmental consequences of a decision or change. This paper presents a structured literature review of the evolution, methodological distinctions, applications, and ongoing debates surrounding ALCA and CLCA. By comparing key studies, standardization efforts, and recent sector-specific applications, we highlight the strengths and limitations of each approach and outline recommendations for future research and practice.

Keywords: Attributional LCA; Consequential LCA; GHG Protocol Standard; Environment; Carbon

1. Introduction

The distinction between attributional and consequential life cycle assessment has been central to the development of environmental systems modeling. While both approaches follow the framework defined in ISO 14040 and ISO 14044 (ISO, 2006), they diverge in their philosophical foundation and modeling intent. Attributional LCA (ALCA) answers the question: "What is the environmental burden associated with producing and using a product as it exists today?" Consequential LCA (CLCA), on the other hand, asks: "What are the environmental consequences if a decision is made to change a system?" (Weidema, 2003; Ekvall and Weidema, 2004). This conceptual split has led to diverging practices, data requirements, and applications across industry and policy domains.

2. Methodological foundations

Attributional LCA is typically based on average data and allocates impacts to products according to physical or economic relationships. This method is well-suited for product labeling, supply chain footprinting, and environmental performance benchmarking (Finnveden et al., 2009). It often involves the use of cut-off criteria and allocation procedures to handle multi-output processes, such as co-products in refining or chemical production.

Conversely, CLCA relies on marginal data and models market-mediated responses to changes in demand. It accounts for broader system effects, including indirect impacts and substitutions (Plevin et al., 2014). Rather than allocating burdens, CLCA expands the system boundary to include processes that are affected by the decision under study. For example, substituting conventional diesel with biofuel may reduce direct emissions but cause land-use changes elsewhere—an effect CLCA aims to capture (Searchinger et al., 2008).

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Recent advances have aimed to formalize these differences. The ILCD Handbook (EC JRC, 2010) and guidance from projects like consequential-lca.org have proposed structured methods for CLCA, while hybrid models attempt to reconcile the two approaches for complex systems.

3. Applications across sectors

ALCA remains the dominant methodology in corporate sustainability reporting and environmental product declarations (EPDs). It underpins the GHG Protocol Product Standard (WRI and WBCSD, 2011), and is widely used in databases such as Ecoinvent and GABI. Industries prefer ALCA for its transparency and replicability, particularly in comparative product assessments and carbon footprint disclosures (Laurin and Jönbrink, 2016).

In contrast, CLCA is increasingly applied in policy and technology impact studies. In energy systems, for example, the environmental benefit of renewables is often underestimated using ALCA, as grid-average emissions mask the displacement of marginal fossil-based generation. Studies by Hertwich et al. (2015) and Pehnt (2006) show that CLCA more accurately reflects the avoided emissions from deploying wind and solar power under decarbonization scenarios.

Similarly, in biofuels, ALCA often neglects indirect land-use change (ILUC), which CLCA explicitly incorporates. Research by Searchinger et al. (2008) and subsequent modeling by the International Food Policy Research Institute (IFPRI) show that these indirect effects can negate the climate benefits of certain first-generation biofuels.

Emerging applications also include carbon dioxide removal (CDR) and offsetting. A recent paper by Anderson and Peters (2022) argued that attributional LCA is unsuitable for assessing the net climate benefit of carbon removal technologies, as it fails to capture the permanence, additionality, and displacement effects inherent to these systems. They advocate for a consequential modeling approach that reflects the dynamic interaction between emissions and removals.

4. Key Debates in the Literature

A longstanding debate surrounds the appropriateness of each approach for decision-making. Proponents of ALCA argue that it is more consistent, auditable, and suitable for product comparisons, especially in supply chains where data availability is limited (Reap et al., 2008). Critics counter that ALCA is descriptive, not predictive, and therefore insufficient when used to guide investment or policy decisions that alter system behavior (Zamagni et al., 2012).

CLCA, though more reflective of real-world dynamics, faces criticism for its complexity, dependency on assumptions, and lack of standardization. Its reliance on economic models, market elasticity, and scenario analysis introduces significant uncertainty, which can hinder its uptake in regulatory settings (Plevin et al., 2014). Nonetheless, the European Commission has shown increased interest in CLCA for guiding product policy under the Circular Economy Action Plan, particularly in contexts like border carbon adjustment and energy labeling (EC, 2021).

A middle ground has emerged through hybrid approaches. These include time-differentiated LCA, consequential-influenced ALCA, and dynamic LCA. Such methods aim to provide the decision-relevance of CLCA with the transparency and consistency of ALCA (Cucurachi et al., 2021).

5. Conclusion and Future Directions

The choice between attributional and consequential LCA is not merely technical it is deeply tied to the purpose of the assessment. If the goal is to understand the current environmental profile of a product or service, ALCA is appropriate. If the objective is to evaluate the potential impacts of a decision, CLCA is more suitable. The growing availability of marginal datasets, the integration of LCA with economic modeling, and clearer methodological guidance are making CLCA more accessible and robust.

Future research should focus on reducing uncertainty in CLCA modeling, especially around market responses and indirect effects. More work is also needed to harmonize ALCA and CLCA within regulatory frameworks and industry standards, enabling stakeholders to use the right tool for the right question. to work.

Compliance with ethical standards

Disclosure of conflict of interest

No Conflict of Interest to be disclosed. It has been presented at 2025 Exploration and Production Standards API meeting on Oilfield Equipment and Materials - Scottsdale, Arizona

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