Contributions to contribution analysis: structuring and extension of approaches to understanding contributions to impacts in Life Cycle Assessment

Meide, M.T. van der

Chapter 1
Introduction

1.1 Life Cycle Assessment

Life cycle assessment (LCA) has become the main method to calculate the environmental performance of products and services. LCA offers a systems perspective that quantifies environmental impacts from resource extraction to end-of-life, enabling prioritization of improvements and avoiding burden-shifting.

LCA comprises four phases (ISO 14044, 2006): 1) Goal and scope definition, 2) life cycle inventory (LCI) modeling, 3) life cycle impact assessment (LCIA), and 4) interpretation.

Goal & scope definition establishes the intended application, reasons and audience, and specifies the product system, functions and functional unit, system boundary, allocation procedures, LCIA approach, data requirements, and assumptions as needed.

LCI analysis compiles, validates and calculates quantitative inputs and outputs for each included process, relates them to the functional unit, and iteratively refines system boundaries and allocation according to cut-off criteria and sensitivity analysis. Generally, for LCA studies, a large database with many interconnected processes like ecoinvent (Wernet et al., 2016) is used to represent large parts of the economy and complex supply chains, and the most important processes of what is studied are modeled in detail by the practitioner.

LCIA selects impact categories, category indicators and characterization models and calculates category indicator results (characterization), optionally with normalization, grouping and weighting.

Interpretation identifies significant issues from the LCI/LCIA, evaluates completeness, sensitivity and consistency, and then formulates conclusions, acknowledges limitations and makes recommendations aligned with the study's goal and scope for decision-making.

Conducted iteratively, LCA relies on the interpretation phase to surface key issues and guide targeted improvements across the goal and scope, inventory, and impact assessment phases. Clear interpretation is thus essential to improve LCA and translate results into actionable insights for industry and policy.

Many LCA studies today use ecoinvent (Wernet et al., 2016) or databases derived from it (e.g. Agribalyse (Colomb et al., 2015) or *Premise* (Sacchi et al., 2022)) as background processes. Ecoinvent is an LCI database with well over 20000 unit processes which are linked together in an attempt to model the global economy from a life-cycle perspective. This database is used by practitioners who model their own foreground sections of specific interest, and then link those to processes in these background databases, such as electricity production or production of metals. The use of background databases helps to save substantial time for practitioners as they can take such data from a database instead of modeling everything themselves. Moreover, it helps to standardize the field with one major source of data. One challenge of such large databases is developing an understanding of the causal relationships between the foreground processes of the practitioner and impact, where impacts may occur deep in a supply chain.

LCA became even more useful and relevant for policy when the scientific community started to explicitly assess possible impacts of new technologies in the future. While this practice has had several names, prospective LCA (pLCA) is currently most common (Arvidsson et al., 2024). The assessment of new or emerging technologies requires changes to the product systems used in these studies to represent future scenarios. While at first this was often done by altering the most important processes in the foreground, studies should also include changes in the background following the same future scenarios for better consistency, for example, changes in the electricity grid (Mendoza Beltran et al., 2018). At first, tools like Presamples (Lesage & Mutel, 2019) and Wurst (Mutel, 2017b) were used to make large scale changes to databases. By now, *Premise* (Sacchi et al., 2022) has become the most used tool to do this.

Premise allows practitioners to generate futurized versions of the ecoinvent database. It is based on scenarios reflecting high-level storylines on change in the environment and society. These storylines are based on combinations of global warming in Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011) and how well global society adapts to and mitigates climate change in Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014). These storylines are implemented in Integrated Assessment Models (IAMs) which project quantitative results on how large-scale metrics such as Gross Domestic Product, Population and electricity production change into the future. Each IAM has its own modeling approaches to follow certain scenarios. *Premise* finally makes use of these quantitative IAM outputs and maps these outputs to changes in the ecoinvent LCI database. These databases can then be assessed at different combinations of time and scenarios.

Whether a practitioner does ‘conventional’ LCA or takes a more advanced approach like pLCA, it is always important to understand clearly what contributes to impacts in a study and how. Contribution Analysis (CA) is the most common tool that is used to understand contributions while assessing to what level specific processes, flows or other entities such as life cycle stages (e.g., production, use, and end-of-life) or impact scores to weighting contribute to impacts.

Furthermore, in pLCA scenario-driven changes are introduced that influence the pressures and impacts calculated for the future. These scenario-driven changes may shift contributions in non-intuitive ways, increasing the relevance of supporting the interpretation phase with a proper CA. It is hence essential that CA is better structured and understood so that impacts in LCA may be better understood and acted upon.

1.2 Understanding contributions to environmental impacts in LCA

In the interpretation phase of an LCA study, CA is frequently used to gain further insight from the LCA results or learn how to make findings actionable. CA has become essential for accurately understanding, analyzing and communicating LCA results. CA is used for 1) Finding important contributors to impacts (Guinée et al., 2002; Hauschild et al., 2018; James & Galatola, M., 2015; Laurent et al., 2020), 2) Identifying data quality problems or mistakes in modelling (Guinée et al., 2002; James & Galatola, M., 2015), and 3) Selecting parameters for sensitivity analysis (Guinée et al., 2002; Hauschild et al., 2018; Laurent et al., 2020). CA is always applied to analyze the contribution *from* some entity *to* another entity. E.g. the contributions *from* processes *to* characterized results.
Despite its wide use, there is no definition that encompasses all current uses of CA. There are different approaches that take different perspectives to contributions. The availability of different approaches and lacking definition of CA may cause confusing, unclear or even irreplicable results.

Problems related to unclear use of CA undermine the credibility of LCA studies and the entire field.

One important distinction between CA approaches is how they assess impacts. The original approaches that were introduced (Heijungs & Kleijn, 2001; Heijungs & Suh, 2002) assess Direct contributions (Srocka & Montiel, 2021) (e.g. the CO_2 emitted directly from a coal powerplant to produce electricity). This focus on Direct contributions has certainly been useful but, as Heijungs & Kleijn (2001) already noted, limited in scope. These approaches cannot indicate how contributions relate to the studied functional unit. There are newer approaches that aim to solve this limitation of these older approaches, through including Indirect contributions as well (e.g. the CH_4 released during the mining of coal for electricity production to be included as contribution for electricity production). Being able to understand the 'connecting' role of processes (Reinhard et al., 2016) is important, for example, if the electricity production from coal would be replaced with electricity from solar, this would also remove the need to produce the coal for that electricity. Understanding what contributes to impacts and through what ways is essential to be able to reduce these impacts.

As CA approaches are not well structured or defined, not all questions regarding contributions can be answered currently. One example is to analyze the Indirect contribution from a group of processes, such as an entire industry sector or region. Current approaches cannot effectively do this type of analysis. The Hypothetical Extraction Method (Hertwich et al., 2024; Miller & Lahr, 2001), from the field of Input-Output analysis which is neighboring the field of Industrial Ecology (Pauliuk et al., 2017) does provide such insights, though it is unclear if that approach could be adapted to LCA and what insights it could provide.

1.3 Contribution Analysis in prospective LCA

While it is already important in LCA to understand what contributes to impacts, pLCA adds an additional challenge: impacts for the same functional unit will generally change between scenarios and with that, have changing contributions to those impacts as well. With these changes, it becomes important to understand what contributes to these changes. This means not just understanding the total impact change, but deeply understanding how the scenario changes that were made affect impacts, as these causal relationships are often difficult to understand in the complexities of modern LCI databases.

In current pLCA practice, the state-of-the-art is to use *Premise* (Sacchi et al., 2022) as futurized background database. While this tool is highly valuable, there is a strong focus on climate change effects in *Premise* because the IAM source data is mainly focused on climate change scenarios. While climate change is undeniably an important matter, other potential environmental challenges also exist. Examples include sand scarcity, water scarcity, or decreases in biodiversity.

Prospective LCA case studies are a good way to learn more about CA since they include the additional challenge of interpreting changing scenarios. While many sectors are already included in *Premise*, the potential future environmental impacts of many more products and services must still be studied to help gain insight into possible problems and steer policy. While there is currently no set way to prioritize what materials to study first, it makes sense to study materials with one or more of these three qualifiers: 1) materials that have high impacts per unit produced, 2) materials that are produced in large quantities or 3) materials that could see major changes in how or how much they are produced.

Cobalt is one example of a material that while not produced in large quantities, is expected to see demand increases up to 10-20 times up to 2050, depending on the scenario (Deetman et al., 2018). Cobalt is generally co-produced with copper or nickel and is used in Lithium-Ion batteries. With large increases in electric mobility and use of mobile electric devices such as laptops and smartphones, demand will increase.

As this is a material with relatively low production volume and strong expected growth in demand, it is interesting to assess how the contributions to the life cycle environmental impacts of cobalt production could change in future scenarios like ore grade decline or shifts in electricity production.

Contrastingly, sand and gravel are two products with a low per-unit impact and very high production volumes. Furthermore, another issue is the growing scarcity of sand and gravel used in construction (Giljum et al., 2000; Ioannidou et al., 2017; Peduzi, 2014; Torres et al., 2017). Sand and gravel are key components of concrete and need to meet stringent quality standards to be fit for this purpose. With an expected growing demand for concrete for the coming decades (Deetman et al., 2020; Watari et al., 2023), alternative sources of sand and gravel may need to be found and it is important that these do not pose negative environmental trade-offs. As these materials have low per-unit impacts but high production volumes, the production of sand and gravel is a contrasting case to the production of cobalt to further assess CA in practice.

Both the extent of changes made to *Premise* and the limited focus on climate change raise a question on how these changes affect LCA results from these futurized LCI databases. While it is documented clearly *what changes* are made on the inventory level in *Premise*, because of the network relationships between processes, it remains unclear *what effects* these changes have throughout *Premise* databases on LCA results. Assessing the contributions from aggregated production sectors to a variety of products can provide a deeper understanding of both CA and the effects different scenarios of *Premise* have in pLCA.

1.4 Problem statement and Research question

The analysis in the sections above lead to the following problem statement. LCA is a key method to understand environmental impacts but improvements can still be made to the method. Amongst others, CA in LCA needs to be better understood. First of all, CA approaches need to be structured and where needed formalized. An overarching definition of CA that encompasses current uses and a consistent terminology in approaches needs to developed such that LCA practitioners can better communicate their results and understand the results from other practitioners. Furthermore, since current CA approaches don't offer the ability to assess the Indirect contribution of groups of processes such as industry sectors or regions, it should be studied whether an approach such as the Hypothetical Extraction Method from Input Output Analysis could provide such a role in LCA.

Presenting these CA approaches by developing a structured framework is useful but also has limitations. Applying approaches to CA in practice will provide a richer insight into what works in CA and what doesn't. It is also important to make use of pLCA in these cases since, as discussed before, pLCA provides additional interpretative challenges through changes in scenarios. For this we use the three cases suggested in section 1.3: cobalt, sand and gravel, and a broader analysis for nine commonly used industrial products included in the pLCA tool *Premise*.

In sum, this thesis makes the case for better structuring and defining CA and to extend it with an approach that can include the Indirect contribution from large groups of processes and to learn from CA in the context of pLCA through a variety of case studies.

This thesis therefore investigates the following Research Question:

How can Contribution Analysis be structured and utilized to better analyze environmental impacts in Life Cycle Assessment?

This is answered using the following sub-questions:

1. How can Contribution Analysis be structured and formalized?

2. How can indirect contributions from groups of processes be better quantified and understood in LCA?

3. What can we learn from Contribution Analysis results in practice, applied to prospective LCA of 3 cases?
   - Prospective LCA of Cobalt production
   - Prospective LCA of Sand and Gravel production
   - Prospective LCA of Nine commonly used products from *Premise*

1.5 Outline

This thesis is structured as follows:

Chapter 2 - This chapter provides an overarching definition of CA that covers current uses of the term and structures different approaches. The approaches are demonstrated using a small example case study and the differences between approaches are discussed. Finally, this chapter provides recommendations for practitioners on which approaches to use when and how to report them.

Chapter 3 - Introduction of the Hypothetical Extraction Method to LCA through introducing a four step process and provides the mathematical framework to perform it. HEM is demonstrated as an approach to CA using a small example case study and a larger example using ecoinvent.

Chapters 4-6 are case studies implementing CA in pLCA with the goal to learn from practical application.

Chapter 4 - A case study demonstrating pLCA on the production of cobalt. This case study assesses different future scenarios of cobalt production and demand and models different production variables according to those scenarios. CA is used to assess the Direct contributions to impacts of cobalt production.

Chapter 5 - A case study demonstrating pLCA on the production of sand and gravel. This case study assesses the conventional production and recycling of sand and gravel based on future scenarios. CA is used to assess the contributions to sand and gravel production as well as the contribution of sand and gravel in concrete production.

Chapter 6 - A study where nine important products from the *Premise* database are assessed. This study assesses what actually contributes to impacts of these products and how those impacts change in different scenarios. CA is used to assess the contribution from fifteen industry sectors, both directly and indirectly.

The outline of these core chapters is also shown in Figure 1.1 visually and shows how each of the methodological chapters (2-3) relate to the case study chapters (4-6).

Chapter 7 - Finally, Chapter 7 answers each sub-question based on the preceding chapters and uses this information to answer the research question. The limitations and possible future work based on this study are further discussed, and further reflections are provided.

S-RQ 1
How can contribution analysis be structured and formalized?

S-RQ 2
How can indirect contributions from groups of processes be better quantified and understood in LCA?

S-RQ 3
What can we learn from Contribution Analysis results in practice, applied to prospective LCA of 3 cases?

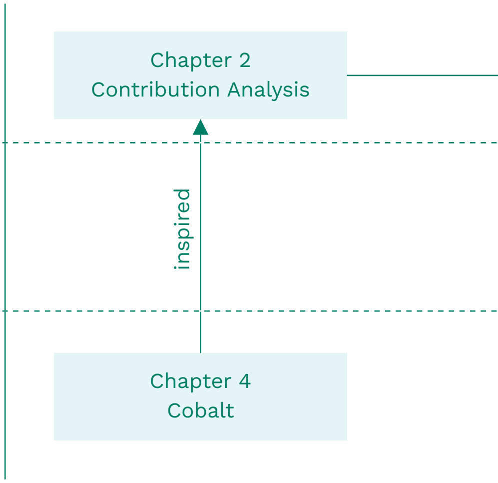
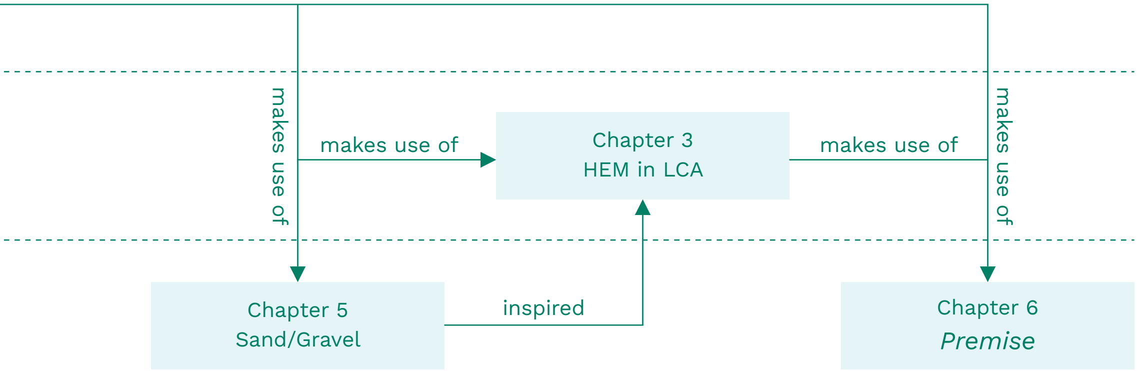


Figure 1.1 - Visual overview of connections between core chapters of this thesis and how they relate to the sub-research questions.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Chapter 3
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