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

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Chapter 7
Conclusions

7.1 Introduction

Life Cycle Assessment (LCA) is widely used to assess environmental impacts. Yet methodological advances remain necessary, particularly in Contribution Analysis (CA), which requires clearer structuring and where missing, formalization. Specifically, the field would benefit from an overarching definition of CA that accommodates current practice and from consistent terminology that enables practitioners to communicate and interpret results more reliably.

In addition, while some current CA approaches can assess both Direct contributions (e.g. CO_2 emitted from electricity production) and Indirect contributions (e.g. the CH_4 released during the mining of coal for electricity production to be included as contribution for electricity production), the analysis of both these perspectives together for large groups of processes could not be done effectively. This could be useful for the analysis of the contribution from industry sectors or countries. It is important to investigate if this problem could be resolved with an additional CA approach. To this end, this thesis investigated if the Hypothetical Extraction Method (HEM) from Input Output Analysis could be used for that purpose.

CA is especially important in the context of prospective LCA (pLCA), where scenario-driven change makes it harder to interpret results. In pLCA, the most used tool to generate future versions of background databases is *Premise* (Sacchi et al., 2022) currently. This tool allows the generation of prospective LCI databases based on storylines that prescribe 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 from these scenarios into the future. *Premise* finally makes use of these IAM outputs and maps them to changes in the ecoinvent LCI database. With the numerous scenario changes *Premise* can include, it becomes more important to deeply understand what contributes to impact changes.

To evaluate and assess the specific challenges different approaches to CA pose and learn how they could be overcome, this thesis applied CA in three pLCA cases.

These cases were chosen for the following reasons: 1) cobalt production given its low production scale but high expected change in demand; 2) sand and gravel production, given concrete demand and the vastly larger production scale relative to cobalt; and 3) evaluation of the pLCA tool *Premise* via analysis of nine commonly used industrial products to clarify drivers of future impacts. Overall, the real-world application of CA in pLCA is a necessary step to improve understanding of CA.

Via this, this thesis aimed to realize the following main objective: to structure and -where necessary- formalize CA and to learn from practical cases so that this toolbox of approaches becomes more useful to LCA practitioners. So, based on the above, this thesis investigated the following Research Question and sub questions:

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

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*

The following sections provide the key findings and conclusions to this thesis. In section 7.2, the three sub-questions posed in the introduction are answered which lead to the answer to the research question. Next, other contributions from this thesis are discussed in section 7.3. Next, some of the limitations and potential future work related to this thesis are presented in section 7.4. Finally, section 7.5 discusses some reflections and implications of this thesis.

7.2 Answers to Research Questions

7.2.1 Sub Question 1: How can Contribution Analysis be structured and formalized?

Chapter 2 answered this question through reviewing existing literature on the theory of CA and analyzing how CA was applied in literature. Each of the existing approaches was structured into five Direct and three approaches where Direct and Indirect perspectives are combined (Direct+Indirect). This led to eight approaches which were discussed and compared both following a single simplified case study designed to highlight differences and through their mathematical formulation. Furthermore, when CA is used, it should be described as contributing *from* something (e.g. a process or EF) *to* something (e.g. LCI or a characterized result).

To start with, while many similar definitions or descriptions of CA existed, none of them accurately and fully described CA. Chapter 2 therefore proposed a new definition which should better cover most cases. This definition was extended from the definition given by ISO 14044 (2006) and Guinée et al. (2002): *A step of the Interpretation phase to assess the contributions from entities like individual life cycle stages, (groups of) processes, elementary flows and indicator results to the overall (or a partial) LCI or LCIA result (e.g. as a percentage).*

Furthermore, Chapter 2 identified eight approaches to CA and defined them carefully. allowing for easier comparison and understanding. A main differentiation between approaches being either Direct or combined Direct+Indirect perspectives is used. Direct contributions are the contributions caused by the elementary flows (EFs) *from* a process where those flows occur (Srocka & Montiel, 2021). For instance, the CO^{2} emitted *from* electricity production by burning coal in a power plant is a Direct contribution from the process 'electricity production with coal'. In contrast, Indirect contributions are the contributions caused by the production *from* an intermediate flow (e.g. a product) from a process, this would include the contributions *from* all EFs of all processes *Indirectly* needed to produce that product in the required amount (e.g. the CH^{4} released during the mining of coal for electricity production to be included as contribution for electricity production).

The five Direct approaches are:

- **Individual Elementary Flow (EF) CA** from specific individual EFs from single processes (Individual EF CA),
    - › e.g. the contribution from CH_4 emission from a single process 'coal mining'.
- **EF CA**, from one EF across all processes,
    - › e.g. the contribution from all CO_2 flows from all processes in the system.
- **Process CA**, from all EFs per process,
    - › e.g. the contribution from all EF (CO_2, CH_4 etc.) from the process 'electricity production from coal' to Climate Change impact.
- **EF group CA**, from groups of EF,
    - › e.g. the contribution from a group of all carbon containing flows.
- **Process group CA**, from groups of processes,
    - › e.g. the contribution from all 'electricity production' processes.

Three combined Direct+Indirect approaches have also been introduced:

- **First-Tier CA**, measuring the Direct contribution from the Functional Unit (FU) process and Direct+Indirect contribution from each intermediate flow of the FU,
    - › e.g. the contribution from 'aluminium production' and contribution from all intermediate flows needed for 'aluminium production' like 'electricity' and 'bauxite'.
- **Life Cycle Stage CA**, from life cycle stages,
    - › e.g. the contribution from life cycle stages like 'production', 'use' and 'end of life'.
- **Path CA**, contributions from a path (e.g. value chain) of processes, often visualized in Sankey diagrams,
    - › e.g. the contribution *from* intermediate flows throughout the product system lead to the final LCA score, showing the 'path' of contributions.

Each of these approaches provides a unique perspective into results of an LCA. Combining approaches can provide deeper insights into results as well.

Finally, guidance was formalized for practitioners on how to report and present their CA methodologies and results, such that LCA studies could become more replicable and interpretable.

In total, the work in Chapter 2 should contribute to higher quality and more reproducible CA's in LCA literature and by this, result in better founded conclusions of LCAs.

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

Chapter 3 answered this question by investigating if and how the Hypothetical Extraction Method (HEM) earlier developed and applied for Input Output Analysis (IOA) (Hertwich et al., 2024; Miller & Lahr, 2001) could be used in LCA. When used in an LCA context, HEM could be described as 'assessing the Direct and Indirect contribution from processes -or groups of processes- to the impact of other processes'. While other CA approaches could show the Direct and Indirect contributions of single processes or life cycle stages, the HEM allows practitioners to assess the Direct and Indirect contribution of groups of processes, such as industry sectors or regions. With HEM, groups of processes are not necessarily connected through their flows such as with life cycle stages. For example, in an LCA of steel production, the HEM approach could be used to assess the Direct and Indirect contribution of transport, independent of which production step the transport is related to. The HEM approach was demonstrated in this chapter through introducing four steps to perform HEM in LCA and formalizing the mathematical approach for these steps and showing these results in a simple case study comparison with other CA approaches.

Making use of HEM in LCA specifically provides more insights in cases where an Indirect perspective is required on groups of processes such as industry sectors or regions. While other existing CA approaches have their own advantages, they could not provide this perspective. With direct process group CA, only Direct impacts were included. With First Tier CA, only the FU and flows to the FU could be assessed. With Life Cycle Stage CA, processes need to be connected through their intermediate flows to form stages (e.g. if we consider the last example, a single life cycle stage could not encompass all different 'transport' instances). Path CA can show contribution paths through intricate supply chains, but cannot combine groups of processes. As each of these approaches helps take a different perspective and answer different questions, HEM is not a replacement of any approach but rather an additional approach to take a different perspective on results.

The approach was not only introduced as a theoretical concept but also in terms of mathematical steps to follow the procedure and includes examples in Excel to reproduce results and contains Brightway2 compatible code so practitioners may re-use this approach in their own work.

7.2.3. Sub Question 3: What can we learn from Contribution Analysis results in practice, applied to prospective LCA of 3 cases?

Three case studies were conducted:
- Prospective LCA of Cobalt production
- Prospective LCA of Sand and Gravel production
- Prospective LCA of Nine commonly used products from *Premise*

This question was answered by making use of CA in three separate case studies, each with different topics. The first was a pLCA study on the production of cobalt, in this study, process group contributions were used to assess the contributions to cobalt production impacts. The second was a pLCA study on the production of sand and gravel for concrete production, in this study process group contributions and first-tier (product) contributions were used. In the third study, nine different products from *Premise* were assessed, process group contributions and HEM from the same fifteen groups were applied.

7

Findings from a study on cobalt production (Chapter 4)
Cobalt production was assessed with pLCA under two different scenarios from 2020-2050 and with four combinations of production variables like ore grade decline and market shares in each of the two scenarios. Process group CA was used to assess what the main contributing process groups were in each of these variable-scenario combinations. The processes were grouped based on the products they produce (e.g. all processes producing 'electricity' were grouped together).

This case study provided the main learning that led to the structuring of CA. This study showed that CA should be executed in a more structured manner, to avoid findings that are less-replicable and with less insight into the contributions to impacts. Firstly, the methodology section did not discuss how CA would be performed -though the code in the Supplementary Information was provided-, this made replication more difficult. Furthermore, process group CA was used, though the groups were not well defined and the approach was mis-named as process

CA. Together, these reflections lead to the realization that CA needs to be better structured and approaches need to be communicated clearly.

Findings from a study on sand and gravel production (Chapter 5)
The impacts of sand and gravel production were assessed with pLCA in two scenarios from 2025-2050 assuming different amounts of recycling. The study integrated new recycling processes into the pLCI database and connected this to sand and gravel markets in 26 regions globally, meaning all processes making use of those products would consume the recycled materials. Process group and First-Tier contributions were assessed. These CA approaches were used to assess how conventional production and production from recycling lead to different contributions and to show the effect of sand, gravel and cement on concrete production.

This case study provided as a main learning that current combined Direct and Indirect approaches cannot effectively be applied to large groups of processes. While the First-Tier CA approach is useful to assess the contribution sand and gravel have on concrete production, the focus was on a single 'concrete production' process. This analysis could have been performed on all concrete production processes and all sand and gravel production processes in unison with an approach that could measure the Indirect contribution of groups of processes. Other existing approaches like Life Cycle Stage CA would also not be effective here, as there are many different parallel production routes that could not be mapped to a single stage, however, this might have been possible by grouping life cycle stages. Path CA was not possible for a similar reason, since it requires the analysis of many processes, which cannot be counted together in this approach. These conclusions have led to the implementation of the Hypothetical Extraction Method in LCA presented in Chapter 3.

Despite the limitations of First Tier contributions, it was still possible to provide deeper insight into the total contribution of sand and gravel to the total impact of concrete production. Furthermore, the CA approach was described in the methodology section, making the study more replicable. Providing these insights and methodological structuring were made possible through the work presented in Chapter 2.

Findings from an analysis of several Premise products (Chapter 6)
Nine different products from *Premise* were assessed. Three pLCI

databases were generated with *Premise* to model one base 2020 scenario and two future scenarios for global warming for 2050 from the IMAGE IAM (Stehfest et al., 2014). While it is clear *what* changes *Premise* makes to LCI databases, it remains unclear *what effect* these changes have on environmental impacts and what the main contributions to those impact changes are. A range of products relevant for industry (Electricity, Heat, Road Transport, Steel, Aluminium, Copper, Concrete, Organic Chemical and Inorganic Chemical) were used to assess these impact changes. Process group CA and HEM were used to assess the contribution from fifteen large product groups representing industry sectors producing similar products. These CA approaches were used to assess the Direct and combined Direct+Indirect contribution of these groups to the nine products.

This case provided as main learning that when the contribution from large groups of processes is assessed, it is important to include both a Direct and combined Direct+Indirect perspectives. With the growth of use of tools like *Premise*, the analysis of changes to an LCI database is important and must be assessed. Process group CA is essential in this assessment to show where contributions (or changes in contribution) originate, however, the use of HEM allowed the finding that some sectors play an important role as 'connecting' sectors. These connecting sectors/processes don't necessarily have high contributions themselves, but 'connect' to other processes in the product-system that do through a causal link, e.g. one finding from this study could be the sector 'ore mining and processing' for copper production, which has a low direct climate change contribution, but connects to other sources of impacts such as electricity needed during the mining and processing. If in this case the mining and processing would use less electricity, or from different sources, the impacts may change substantially, this only becomes apparent through including an Indirect perspective. This analysis of Indirect contributions from large process groups was possible through adapting HEM from IOA into LCA in Chapter 3.

Summarizing the learnings from all three cases; the cases show it is important to define clear categories of CA approaches and develop a new approach to analyze the Indirect contribution of large groups of processes in the form of HEM. The practical insights given through performing pLCA in a variety of case studies and critically assessing the possibilities and limitations of CA made it possible to develop this structuring and convert the HEM approach to LCA.

7.2.4. Answering the main research question

Through answering the sub-questions above, it now becomes possible to answer the Research Question:

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

Through dividing CA approaches into two groups of perspectives, *Direct* and *Indirect* and clearly describing how these approaches should be applied *from* some entity *to* another entity CA has been better structured. Furthermore, other approaches may in the future be added into this framework, such as HEM, which was introduced in this thesis for LCA as well. This structure gives practitioners a common language to discuss CA approaches with and helps practitioners choose which approaches they need for their work.

What can be learned as well from this thesis is that it is highly important for a practitioner to understand what questions a specific CA approach can answer and how that may fit in the goal and scope of their LCA study, to describe the methodological approach of CA used in a study and finally to clearly interpret and describe their results. The relatively unstructured approach in the case-study in Chapter 4 (on cobalt) is a clear example of why this is necessary. Chapter 2 in this thesis suggests a clear and structured approach to CA that was used in Chapter 5 and 6 and can in the future be used by other practitioners in their work.

While CA is a large toolbox of approaches, the various approaches all come with limitations of their own. Practitioners should be mindful of these when they make use of CA. For example with the case-study in Chapter 5 (on sand and gravel) it became clear that existing approaches could not provide the entire insight into the contributions of sand and gravel to other products such as concrete, leading to the development of HEM in Chapter 3, which was utilized for this purpose in the case-study in Chapter 6 (on products in *Premise*).

Furthermore, it also becomes clear from this thesis that the use of multiple CA approaches in studies makes sense in many cases, as this can provide multiple perspectives on the same underlying results. Practitioners should carefully consider which approaches are useful on a case-to-case basis to answer their research questions. This was discussed in Chapter 2, but the benefit of taking multiple perspectives to the results of a study are also shown in the case-studies in Chapter 5 (on sand and gravel) and Chapter 6 (on products in *Premise*). The combination of different perspectives, especially combining Direct and Indirect approaches allows for a deeper understanding of LCA results.

7.3 Other contributions of this thesis

In addition to structuring and formalizing CA approaches and introducing HEM to LCA, other contributions have also been made to the pLCA field through the three case-studies from Chapter 4-6.

In the study on cobalt production (Chapter 4), a new ore grade decline model was developed, which models changes in inventory data based on the demand for cobalt. Previous approaches that modeled ore grade decline did so based on progression of time, while in future scenarios regarding the energy transition, it is important to consider the demand for such materials, as those are closely related to the scenario in which they are used. This ore grade decline model was later used in Xu et al. (2022).

In the study on sand and gravel production (Chapter 5), a dynamic stock model was developed to model the recycling of sand and gravel based on how much material becomes available from the building stock and how much demand there is for new buildings. While dynamic stock modeling is not new, this has not yet been applied to assess the recycling potential of gravel and sand in this manner. This recycling model determines the market share between conventional and recycled production. Furthermore, this was integrated into a 'community scenario' for *Premise* such that other LCA practitioners making use of *Premise* can import and use this scenario in their own studies.

Finally, other contributions that may be useful for the LCA community have been made for the work done in this thesis in the form of code contributions to enable CA in the Activity Browser (AB) software (Steubing et al., 2019). While these contributions may not be considered scientific contributions as such, they benefit the scientific community by enabling practitioners to do CA. Contributions relevant to this thesis were the following: Co-authoring the first implementation of CA in AB[3], adding

First-Tier contributions to AB[4] and adding new options for cut-off calculations, in line with PEF regulation (JRC, 2018)[5].

7.4 Limitations and Future Work

One limitation to this thesis, and primarily Chapter 2 and the case studies (Chapter 4-6) is that only CA approaches in literature were studied. LCA is an applied field, and many LCA software alternatives exist, each with their own features. With this spread of software options also come different approaches to CA that are not found in literature, for example a 'Path CA' alternative in SimaPro[6], for which no clear public documentation exists for this approach to be replicated or verified to be correct. Contrastingly, OpenLCA makes use of a modified version (M. Srocka, personal communication, May/June 2025) of the path CA approach (Srocka & Montiel, 2021). While the approach is not clearly communicated in documentation[7], the code is open source and can be reviewed.

The spread of different software implementations for different CA approaches is a risk for LCA practitioners as it may be unclear what approach is really performed 'behind the screens' and for practitioners to verify if the approach is correct. Future work could potentially review different approaches in software based on the same case study implemented everywhere such that results can be compared and the approaches could be 'reverse engineered'. An alternative solution could be for LCA software developers to open their algorithms so their working may be verified. LCA software is the 'lab equipment' of LCA practitioners and the ability to verify the functioning of this equipment is essential for trust in the findings generated in this field.

Another limitation in this study is that CA is only demonstrated to characterized results (e.g. after the conversion from CO_2 and CH_4 emissions to 'climate change impact'). While most studies currently are concerned with characterized results, the inventory, normalized and weighted results should not be forgotten in LCA. Chapter 2 and its Supplementary Information discuss these other entities somewhat, but future work should also more deeply consider CA approaches to other entities. This is also relevant for more complex assessments, such as the recently introduced TimeEx (Müller et al., 2025), where contributions from different time periods become relevant.

While this thesis is able to provide some generalized recommendations on CA approaches, a limitation here is that it is not possible to recommend a specific approach or combination that applies to all cases. A practitioner needs to determine based on the requirements of their cases which approaches to use to provide the insights they need. Future work could focus on more specific recommendations for e.g. specific sectors or product groups with similar requirements in their assessment.

7.5 Reflections and Implications

LCA has become an important method in understanding the environmental impacts of products and services and LCA is still gaining importance in the policy landscape, for example in the European Union with Product Environmental Footprint (PEF: JRC, 2018) and the Carbon Border Adjustment Mechanism (CBAM)[8]. When looking at PEF, it is recommended to make use of CA to identify important entities for sensitivity analysis. Among these entities, life cycle stages are mentioned, but it is never defined how these should be assessed. Furthermore, a cumulative cut-off of 80% (sorted by highest contribution, counting up to 80%) need to be used for sensitivity analysis, though it is never made clear how to manage negative emissions. While the PEF is certainly a step in the right direction for including such guidelines in the first place, it is also clear improvements still need to be made to improve the standard, e.g. by clarifying how to deal with negative contributions.

Prospective LCA specifically is also relevant to help steer technology development and decision making for future technologies and could help prevent lock-in effects where a sub-optimal technology is adopted. While not directly related to policy through standards like PEF or CBAM, results from pLCA studies can be important in the shaping of policies or regulations to steer industries in a cleaner direction. Results from pLCA studies can be used to assess possible futures and what actions need to be taken to steer toward desired future scenarios. pLCA must keep developing and the CA tools to understand results must keep developing as well.

Through the introduction of CBAM and other policies that require LCA, more LCA practitioners are needed and more decision makers are required to understand LCA results. 'LCA literacy' is therefore an important topic that must be expanded to these new groups of practitioners and decision makers. This thesis, but specifically Chapter 2, could help increase this literacy.

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[3] *https://github.com/LU-CML/activity-browser/commits/Results_Analysis/*

[4] *https://github.com/LCA-ActivityBrowser/activity-browser/pull/1046*

[5] *https://github.com/brightway-lca/brightway2-analyzer/pull/326*

[6] *https://support.simapro.com/s/article/The-Network-Tab-in-SimaPro*

[7] *https://greendelta.github.io/openLCA2-manual/res_analysis/res_sankey.html*

[8] *https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism/cbam-legislation-and-guidance_en*