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

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Summary

Life Cycle Assessment (LCA) is the primary method for evaluating environmental performance across a product's life cycle, with the interpretation phase being critical for identifying significant issues and guiding improvements. Contribution Analysis (CA) is the main tool for understanding how processes and flows contribute to overall impacts, yet despite its importance, CA is not well standardized.

CA is widely used in LCA interpretation to identify key contributors to impacts, detect data quality issues, and select parameters for sensitivity analysis. However, CA lacks an overarching definition and structured methodology, leading to inconsistent and sometimes irreproducible results and a lower credibility of LCA studies. Various approaches to CA exist and can assess two different sides: Direct contributions (e.g. CO_2 emitted from electricity production) and Indirect contributions (e.g. CH_4 emitted during coal mining for the production of electricity from coal). Each approach can assess one or both of these sides from a different perspective.

For large groups of processes however, combined Direct and Indirect CA cannot be easily applied. However, the Hypothetical Extraction Method (HEM), used in the field of Input Output Analysis, in principle is capable of providing such a perspective on CA. It was however unclear if that approach could be adapted to LCA and what insights it could provide.

CA is especially important in the context of prospective LCA (pLCA), where scenario-driven change in the data makes it harder to interpret results. In pLCA, the most used tool currently is *Premise* to generate future versions of background databases based on scenario storylines. To learn about the specific challenges that 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.

In this way, 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.

Chapter 2 provides an overarching definition of Contribution Analysis that covers current uses of the term and structures different approaches. A distinction is made between Direct and Indirect contributions, The different approaches are demonstrated using an example case study and the differences between approaches are discussed. Each of these approaches provides a unique insight into results in LCA. Five direct and three combined Direct and Indirect approaches are described.

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.

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. Primarily, 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). The work in Chapter 2 should contribute to a higher quality and more reproducible body of LCA literature and more well-founded conclusions.

Chapter 3 introduces the HEM to LCA through outlining a four step process including a mathematical framework. HEM is demonstrated as a CA approach using a small example case study and a larger example using ecoinvent. Making use of HEM provides insights in cases where an Indirect perspective is required and for groups of processes such as industry sectors or regions. While other existing approaches have their own advantages, they could not provide this perspective effectively. The work in Chapter 3 shows how and when HEM can be a useful approach for CA in cases where current CA approaches may be lacking, such as assessing the Direct and Indirect contributions from groups of processes, providing an additional CA approach to the LCA practitioner in understanding impacts from their systems.

Next, Chapters 4, 5 and 6 are three case studies that make use of CA with the intent of learning from applying CA in practical cases. Chapter 4 is a case study demonstrating pLCA on the production of cobalt. 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 electricity production). This case study provided the main learning that led to the structuring of CA in Chapter 2. Chapter 5 is a case study demonstrating pLCA on the production of sand and gravel. Process group and First-Tier contributions (contribution of intermediate products to concrete production) were assessed. These CA approaches were used to assess how conventional production and production from recycling lead to different impacts and to show the contributions from sand, gravel and cement to concrete production. This case study provided as a main learning that current combined Direct+Indirect approaches cannot effectively be applied to large groups of processes, HEM as introduced in Chapter 3 helps provide this perspective in LCA. Chapter 6 is a study where nine important industrial products from the *Premise* database are assessed. CA via process group CA and HEM were used to assess the effect from fifteen large product groups representing industry sectors producing similar products. The CA approaches were used to assess the Direct and combined Direct+Indirect contribution of these groups to the nine products. Process group CA is essential in this assessment to show where contributions (or changes in contribution) originate. 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 have high contributions. This analysis of Indirect contributions from large process groups was possible through adapting HEM from IOA into LCA in Chapter 3. Together, the learnings from all three cases show it is important to define clear categories of CA approaches and develop a new approach to analyze new perspectives when relevant, such as HEM.

To conclude, 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. This structure gives practitioners a common language to discuss CA approaches with and helps practitioners choose which approaches they need for their work.

It is important for a practitioner to understand how CA 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. While CA is a large toolbox of approaches, the various approaches all come with limitations of their own, which practitioners should be mindful of when they make use of CA. Finally, it also becomes clear from this thesis that the use of multiple approaches to CA in studies makes sense in many cases, as this can provide multiple perspectives and deeper insights on the same results.

It should be noted that in this thesis only CA approaches in literature were studied. LCA is an applied field, and many LCA software alternatives exist, each with their own features. These software options should be better studied as well. 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. Furthermore, this thesis has a focus on CA is applied 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, making use of CA for the inventory, normalized or weighted results can also provide useful insights and should not be forgotten in LCA.