Universiteit Leiden
The Netherlands

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Meide, M.T. van der; Heijungs, R.; Guinée, J.B.; Hu, M.; Steubing, B.

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CRITICAL REVIEW

Contribution analysis in LCA: an overview of approaches and when to apply them

Marc van der Meide[1] · Reinout Heijungs[1,2] · Jeroen Guinée[1] · Mingming Hu[1] · Bernhard Steubing[1]

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Abstract

Purpose Contribution analysis (CA) is an essential method to understand and communicate life cycle assessment (LCA) results. Different approaches to CA have been used to answer different questions. However, it is often unclear which approach is used in LCA studies, leaving confusion as to how contributions are actually assessed. This makes a correct interpretation or replication difficult and can even lead to ill-founded conclusions. This study aims at a clear terminology for transparent CA communication.

Method First, we introduce eight approaches to CA used in the literature. Then, we introduce an example case study to compare each CA approach against. We then discuss the eight approaches, discussing *from* what and *to* what they contribute. We also make a distinction between the *direct* and *indirect* perspectives, where *direct* contributions are *from* elementary flows (EF) of processes, while *indirect* contributions are *from* all EF of processes contributing to the intermediate flows (products).

Results and discussion We identify and describe several approaches for *direct* CA: (a) Individual elementary flow CA, for specific individual EFs from single processes (individual EF CA). (b) EF CA, for one EF across all processes, e.g. all CO_2 flows. (c) Process CA, for all EFs per process, e.g. contribution to climate change impact *from* the process ‘electricity production from coal’. (d) Grouping can also be applied to these approaches, e.g. process group CA for all ‘electricity production’ processes. *Direct* and *indirect* contributions can also be quantified. First-tier CA, measuring the *direct* contribution of the functional unit (FU) process and *indirect* contribution of each intermediate flow of the FU. Life cycle stage CA, e.g. calculating the contributions of life cycle stages like ‘production’, ‘use’, and ‘end of life’. And finally, path CA—often visualized in Sankey diagrams—e.g. showing the ‘path’ contributions take to the FU. We compare the results, advantages, and disadvantages of each approach, discuss general limitations of CA, and give recommendations on reporting CA.

Conclusion Our study can help guide practitioners in choosing relevant CA approaches for their studies to gain better insights and more transparently communicate and report their results. This should contribute to a higher quality and more reproducible body of LCA literature and more well-founded conclusions.

Keywords Contribution analysis · Life cycle stage analysis · Life cycle interpretation · Life cycle impact AssessmentHotspot analysis · Sankey

Abbreviations

CA	Contribution analysis
CO_2eq.	Carbon dioxide equivalent
CH_4	Methane
CO_2	Carbon dioxide
EF	Elementary flow
Fig.	Figure
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
IO-LCA	Input-output LCA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PEF	Product environmental footprint
Sec.	Section

✉ Marc van der Meide
m.t.van.der.meide@cml.leidenuniv.nl

[1] Institute of Environmental Sciences, Leiden University, Leiden, The Netherlands

[2] Department of Operations Analytics, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

SI Supplementary information
SO_2 Sulphur dioxide

1 Introduction

Life cycle assessment (LCA) has become the main method to calculate the environmental performance of products and services. The four phases of LCA (goal and scope definition, inventory analysis, impact assessment, and interpretation) are closely intertwined. In the interpretation phase of an LCA study, contribution analysis (CA)—also called hotspot analysis (James & Galatola 2015) and historically called dominance analysis (Heijungs et al. 1992) or gravity analysis (ISO 2006)—is frequently used to gain further insight from the LCA results or how to make this information actionable. For example, manufacturers may want to gain insight into which suppliers or internal processes they can best change to reduce the environmental impacts of their products. Consequently, CA has become essential for accurately understanding, analyzing, and communicating LCA results. CA achieves this through.

- Finding important contributors to impacts—often termed 'hotspots'—that can assist in finding product system improvements (Guinée et al. 2002; James & Galatola 2015; Hauschild et al. 2018; Laurent et al. 2020),
- Identifying data quality problems or mistakes in modelling (Guinée et al. 2002; James & Galatola 2015),
- Selecting parameters for sensitivity analysis (Guinée et al. 2002; Hauschild et al. 2018; Laurent et al. 2020).

Despite the near-universal use of CA in the LCA field, a complete and precise definition of CA is lacking. CA is always applied to analyze the contribution *from* some entity *to* another entity. E.g. the contributions *from* processes *to* characterized results. The ISO 14044 (2006) standard describes CA to determining the contribution *from* life cycle stages or groups of processes *to* the total result (2006 Annex B2.3, p. 36). But in practice, CA has also often been applied to determine the contributions *from* other entities such as elementary flows (EFs), processes, or characterized results. The '*to*' part is notably imprecise and could be the life cycle inventory (LCI) result or any level of life cycle impact assessment (LCIA). Many other descriptions of CA exist in literature, all missing certain entities as with the ISO 14044 (2006) or not differentiating what the analysis contributes *from* or *to* (Guinée et al. 2002; Hauschild et al. 2018; Heijungs et al. 1992; Heijungs & Kleijn 2001; Heijungs & Suh 2002; Klöpffer & Grahl 2014; Laurent et al. 2020; Noh et al. 1998; Reinhard et al. 2016, 2019).

In addition to a complete and precise definition of CA, there are different approaches that take different perspectives on finding contributions. The availability of different approaches and lacking definition of CA may cause confusing, unclear, or even irreplicable results. Examples of these problems can be found randomly in the literature: CA is often not replicable as it is not reported *from* what CA is applied or because processes, process groups, or life cycle stages are not defined or mixed up (Bałdowska-Witos et al. 2020; Battisti & Corrado 2005; Eksi & Karaosmanoglu 2018; Gorrée et al. 2002; Hesser et al. 2017; Leccisi & Fthenakis 2021; Niero et al. 2015; Panepinto et al. 2015; Pradeleix et al. 2015; Roux et al. 2016; Scipioni et al. 2013; Zink et al. 2014). Many of these studies apply life cycle stage analysis with life cycle stages that are not clearly defined. Next, figures from Bałdowska-Witos et al. (2020), Battisti and Corrado (2005), Duan et al. (2022), and Leccisi and Fthenakis (2021) are challenging to interpret. More importantly, Zink et al. (2014) and Pierobon et al. (2018) do not make clear in their studies why the use of contribution analysis would be required to satisfy the goal of their LCA study. Finally, Zink et al. (2014), Pierobon et al. (2018), and Panepinto et al. (2015) share results, but never interpret this data in their studies. Such ill-defined CA applications often lead to non-replicable results, which undermines the credibility of these LCA studies. However, the average LCA practitioner is hardly to blame for this, as there is no clear overview of what approaches exist and how or when to apply them.

Some positive examples of CA in literature exist as well: Examples of well-documented CA are Eksi and Karaosmanoglu (2018), who provide detailed reporting of their methodology and which processes belong to each life cycle stage; Gorrée et al. (2002), who provided substantial discussion of CA results; and Zink et al. (2014), who made good use of figures. Most studies apply CA only *to* impact category results, though some also consider CA *to* other entities like weighted results (Bałdowska-Witos et al. 2020; Duan et al. 2022).

In this study, we aim to structure, explain, and provide a clear terminology for different CA approaches. We believe this will guide LCA practitioners to better understand contribution analysis and the LCA results obtained from CA, help practitioners make more conscious choices regarding CA, and better document and communicate contribution analysis results in future LCA studies. We proceed by introducing a general approach and illustrative case study used to demonstrate all approaches we discuss. We then discuss five *direct* approaches: individual elementary flow contribution analysis, elementary flow contribution analysis, process contribution analysis, elementary flow group contribution analysis, and process group contribution analysis. After this, we discuss three approaches that show both *direct* and *indirect* contributions: tiered contribution analysis, life cycle stage contribution analysis, and path contribution analysis. Finally, we discuss and compare the different approaches to CA.

2 Method

2.1 General approach

For this article, we use a slightly adapted definition of contribution analysis from Guinée et al (2002, p. 110) and ISO 14044 (2006): *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)*. We use the terms and definitions of ISO 14044 (2006) where possible.

From an examination of a small fraction of the body of LCA literature, and from our own experience, we have identified the following general contribution analysis approaches:

- Direct CA, including
  - Individual EF CA,
  - EF CA,
  - Process CA,
  - EF group CA,
  - Process group CA,
- First-tier CA,
- Life cycle stage CA,
- Path CA.

In the following chapters, each approach is described as follows:

- Goal: describes for what the approach may be useful,
- Description: identifies how each approach is performed on a high level,
- Example: example of results, we introduce a simplified LCA case study below that we use across all approaches,
- Advantages and limitations: advantages and limitations specific to the approaches.

We describe and demonstrate each of these approaches in terms of contributions *to* characterized results and discuss contributions *to* other entities like LCI and normalized results in the discussion. We focus on process-LCA (Heijungs et al. 2022) and do not discuss methods exclusive to input–output (IO)-LCA, such as power series expansion (Suh & Heijungs 2007) or the path exchange method (Lenzen & Crawford 2009). We demonstrate each of the approaches in the context of a simplified case study and in the Supplementary Information (SI) 1.7 a system using the ecoinvent database (Wernet et al. 2016) to demonstrate benefits and limitations of these approaches with systems consisting of many more processes and EFs. For each of the approaches, we provide a full step-by-step mathematical description in SI 1 and an Excel file with all calculation steps applied to the case study in SI 2. All results in this study are rounded and may not add up to totals exactly, but the full results are presented in the Excel file of SI 2.

2.2 Illustrative case study

In order to exemplify the different CA approaches discussed in the following, we use a simplified case study. The product system of the simplified case study is comprised of the production and use of a fridge. We use the functional unit (FU) of ‘cooling 10 kg food for 8 years to 6° Celsius’, and we assume that this is the lifetime of the fridge and shorten the FU in the further text to ‘cooled food’. The case consists of six simplified unit processes and two elementary flows, as shown in Fig. 1. The flow amounts of the unit processes are quantified in Table 1. In the simplified case study, we characterize the climate change impact (expressed in kg $CO_{2eq.}$) adopting the global warming potential for 100 years (GWP_{100}) and assuming the GWP_{100} for carbon dioxide (CO_2) is 1 kg CO_2eq./kg CO_2 emitted and for methane (CH_4) is 29.8 kg CO_2eq./kg CH_4 emitted (IPCC 2022). The total climate change score is 976.9 kg CO_2eq. for ‘cooling food for 8 years to 6° Celsius’.

This simplified case study is meant for illustration of different CA approaches only and should not be used to draw any conclusions with regard to the environmental performance of fridge use or any of the other processes presented. Specifically for ‘coal mining’, which has much lower direct CO_2 emissions in reality, and ‘fridge production’, which in our case has CO_2 emissions to represent some polluting process. We consider, e.g. fuel inputs that would cause CO_2 emissions to these processes to be cut-off. We make these unrealistic changes to better demonstrate the different approaches to CA with a simple example, at the cost of some realism. We provide a more realistic case study for the ‘use of a fridge’ using the ecoinvent database (Wernet et al. 2016) in SI 1.7, though that example still meant to illustrate the differences between the different CA approaches, not to assess real-life ‘cooling of food’.

3 Direct approaches to contribution analysis

There are five direct approaches to contribution analysis:

- Individual elementary flow contribution analysis,
- Elementary flow contribution analysis,
- Process contribution analysis,

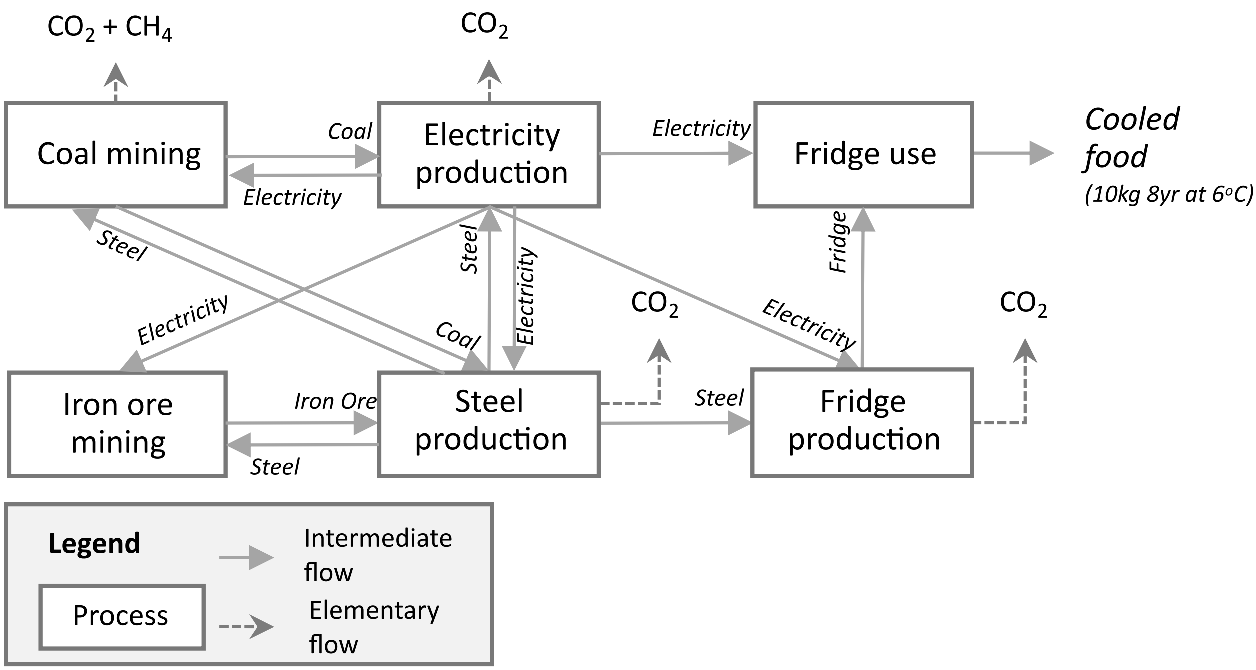


Fig. 1 Product system for the simplified example case, the functional unit is 'cooling 10 kg food for 8 years to 6° Celsius', shortened as 'cooled food'. The system consists of six unit processes and two distinct elementary flows

Table 1 Unit process inventory for the six simplified processes, showing functional, intermediate, and elementary flows for every process. Positive intermediate flows are process inputs; positive elementary flows are process outputs

Process name	Functional flow (product/service)	Intermediate flows	Elementary flows
Coal mining	Coal: 1 kg	Electricity: 0.04 kWh Steel: 0.001 kg	CO_2: 0.05 kg CH_4: 0.01 kg
Electricity production	Electricity: 1 kWh	Coal: 0.4 kg Steel: 0.001 kg	CO_2: 0.8 kg
Iron ore mining	Iron ore: 1 kg	Electricity: 0.1 kWh Steel 0.001 kg	
Steel production	Steel: 1 kg	Electricity: 0.1 kWh Coal: 0.8 kg Iron ore: 2 kg	CO_2: 1.6 kg
Fridge production	Fridge: 1 unit	Electricity: 150 kWh Steel: 40 kg	CO_2: 150 kg
Use	Cooled food: 1 year	Electricity: 75 kWh Fridge: 0.125 unit	

- Elementary flow group contribution analysis,
- Process group contribution analysis.

Each of the direct approaches provides a different level of disaggregation of contributions, providing different insights into the contributions. The direct approaches show only *direct* contributions. *Direct* contributions are the contributions caused by the elementary flows (EFs) *from* a process where those flows occur (Srocka & Montiel 2021), e.g. 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 like 'electricity', from the process 'electricity production') from a process; this would include the contributions *from* all EFs of all processes *indirectly* needed to produce that intermediate flow in the required amount. An example of *indirectly* emitted CO_2 would be CO_2 emitted during the production of steel for the powerplant. In short, *direct* contributions are *from* processes, while *indirect* contributions are *from* other processes contributing through the intermediate flows (e.g. products).

Each of the direct approaches makes use of the same disaggregated result from an LCA and was established over two decades ago (Heijungs and Kleijn 2001; Heijungs and Suh 2002). As the direct approaches are closely related, we discuss the advantages and limitations together at the end of this chapter.

3.1 Individual elementary flow contribution analysis

3.1.1 Goal

Contribution analysis *from* specific individual elementary flows (EF) caused by distinct processes—individual flow contributions in short—represents the most disaggregated approach in contribution analysis.

There are two goals a practitioner can achieve with this approach: either investigate specific individual flows the practitioner may be interested in, or identify which individual flows contribute most to the result. A practitioner could use this to investigate contributions *from* individual elementary flows of specific processes, e.g. the climate change impact *from* CO_2 emitted by electricity production with coal. Another example could be to identify outliers in the data.

3.1.2 Description

This approach is based on the disaggregated results of an LCA calculation. The contributions are calculated such that the format is a matrix with EFs as rows and processes as columns. Each cell in this matrix represents an individual characterized result for the combination of the specific EF and process. We show how this could be calculated in SI 1.3.1. As this matrix contains the disaggregated contributions, we call this the contribution matrix. The contribution matrix shows all *direct* contributions, i.e. the impacts associated with the EFs coming from a process. When all numbers in the contribution matrix are summed, they are equal to the total characterized result.

3.1.3 Example

We show an example of the approach *to* the characterized results *from* individual flows with the example system in Fig. 2B. Subfigure B shows the individual flow contributions in orange for the individual flow contribution *from* CO_2 of 'coal mining'. We also show the results for this approach in a stacked bar chart in Fig. 3A.

3.2 Elementary flow contribution analysis and process contribution analysis

3.2.1 Goal

The goal of the next two approaches is to find the contributions *from* a process or EF. A practitioner could use process CA to investigate contributions from specific processes, e.g. the climate change impact *from* electricity production with coal. A practitioner may use this to identify which processes or EFs in the system have the highest *direct* contributions to climate change.

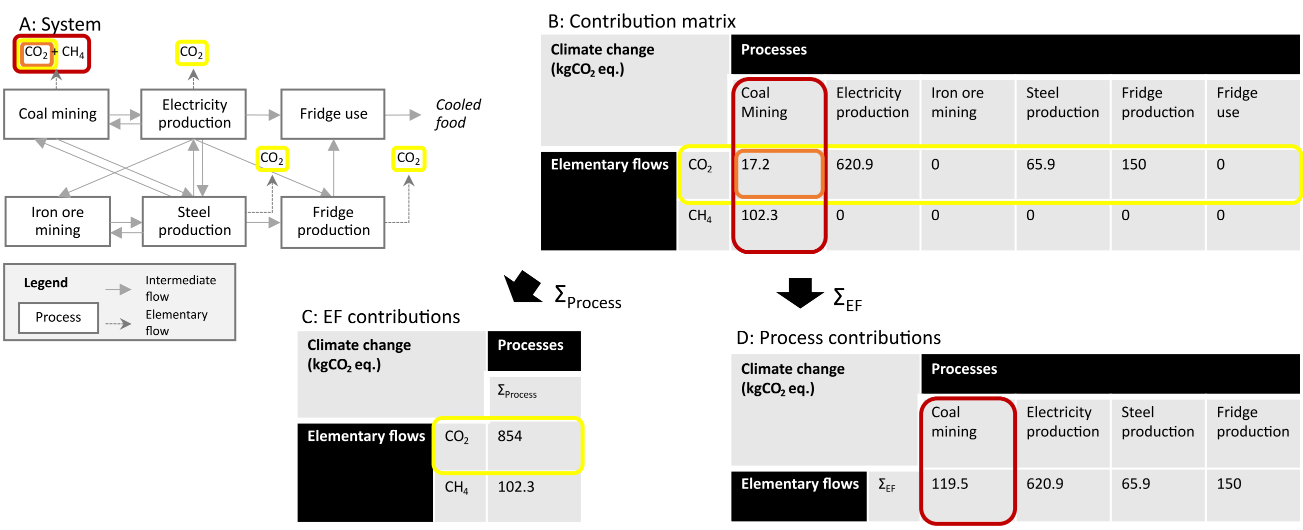


Fig. 2 **A** Overview of the system for the production of 'cooled food'. **B** Contribution matrix, showing the contributions *from* specific individual elementary flows (EF) originating of distinct processes *to* characterized results. The orange entry shows the contribution *from* 'CO_2' of 'coal mining' *to* 'climate change'. **C** EF contributions, showing the contributions *from* EFs *to* characterized results. The yellow entry shows the contribution *from* 'CO_2' *to* 'climate change'. **D** Process contributions, showing the contributions *from* processes *to* characterized results. The red entry shows the contribution *from* 'coal mining' *to* 'climate change'. Note that all impacts are caused from the provision of the FU and all process contributions of 0 have been removed

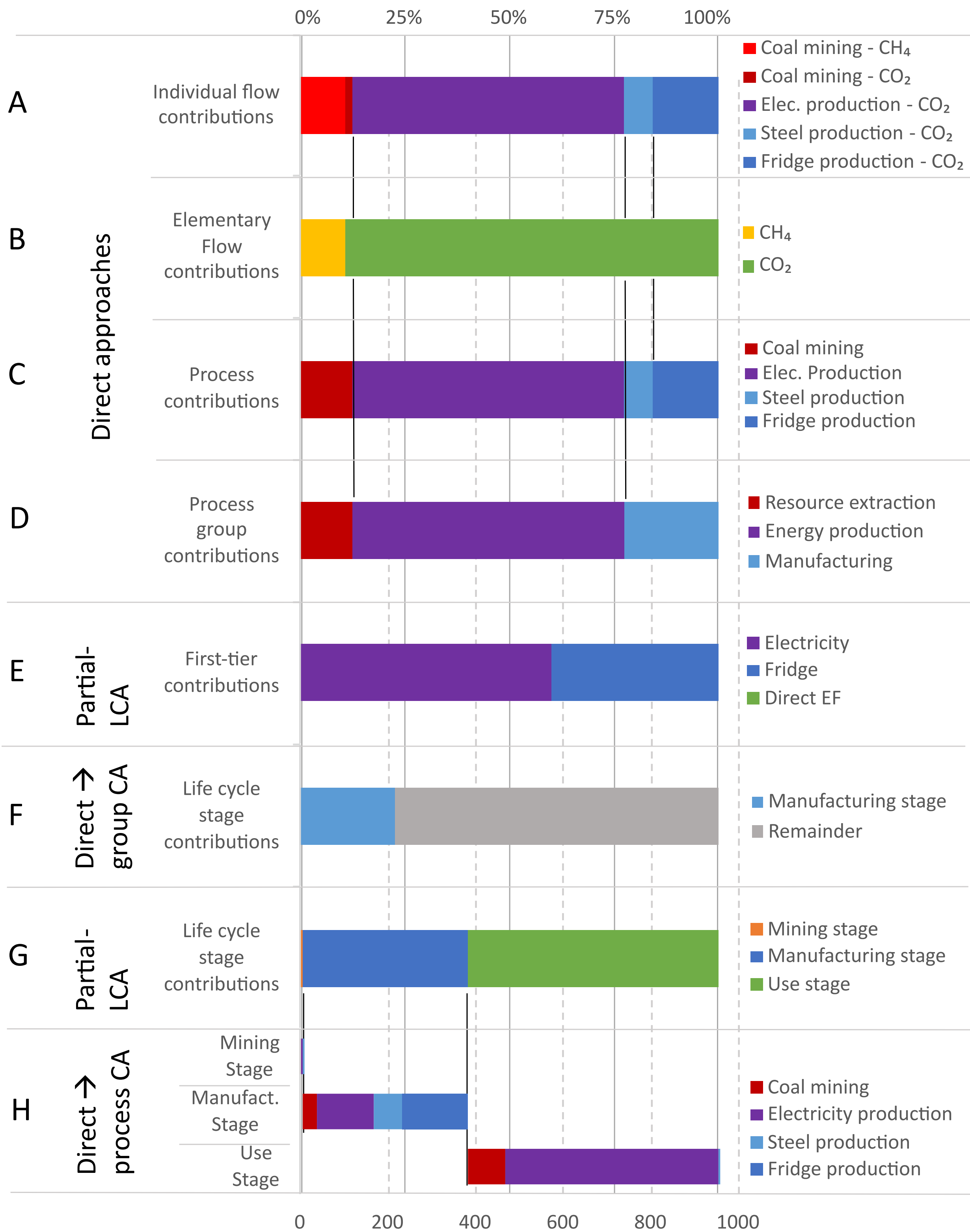


Fig. 3 Different contribution analysis results *to* characterized results of the simplified case study compared. **A** Individual flow CA. **B** EF CA. **C** Process CA. **D** Process group CA. **E** First-tier CA. **F** Group life cycle stage CA. **G** Partial-LCA life cycle stage CA. **H** Process contributions *to* life cycle stages

3.2.2 Description

These two approaches can transparently reduce the amount of generated data from individual flow contribution analysis while still providing a high level of detail.

These approaches are applied by summing one of the two axes of the contribution matrix. For EF CA, the processes (columns) are summed, and one result per EF (row) is left. For process CA, the EFs (rows) are summed, and one result per process (column) is left. This is also demonstrated in SI 1.3.2.

3.2.3 Example

The results for these approaches are shown in Fig. 2C for EF and Fig. 2D for process contributions. The figure shows how the number of results can be effectively and transparently reduced. As an example, the process contributions *from* 'coal mining' are shown in red, and EF contributions *from* CO_2 are shown in yellow. The results are also shown in Fig. 3B and C in context with the other approaches.

3.3 Elementary flow group and process group contribution analysis

3.3.1 Goal

The goal of these two approaches is to find the contributions from a group of EFs/processes. A practitioner could create groups for two reasons: either to transparently reduce the amount of datapoints, or because those EFs/processes are logically connected. A practitioner could use process group CA to assess contributions from a group of processes, e.g. the climate change impact from the process group containing all processes related to electricity production. This approach is useful to find *direct* impacts of related processes (e.g. all transport processes) or EFs and to reduce the amount of data to interpret.

3.3.2 Description

Contribution analysis *from* process groups and EF groups are approaches that exchange levels of detail with a smaller and easier to interpret number of results. These two approaches build on the previous two approaches and reduce the number of results further, aiding in interpretation.

Grouping is done based on metadata. The metadata are attributes about the data, e.g. data about the EF/process. This can for example be done by grouping EFs based on EFs in different compartments, e.g. grouping all CO_2 flows from 'air', 'air, urban', etc. or grouping on an element, e.g. all flows containing carbon. For processes, this can for example be done by grouping with the same product name, location, or other relevant information such as industry sectors (e.g. ISIC sectors in ecoinvent). Such metadata could be provided by LCI database developers or be provided by the practitioner in the form of 'tags', such as 'disposal stage' or 'pesticide'. In SI 1.3.3, we demonstrate a mathematical approach transforming EF or process contributions into grouped results.

When using EF/process groups, the practitioner must be aware that the EF/process must always be in exactly one group. The entity cannot be in more than one group, or it would be double counted. Each entity must also be in one group, or its impact will not be counted. For grouping on pre-existing metadata (like product name), this would not be a problem, but attention should be paid to this when using custom tags, where all entities in a CA need to be tagged. In practice, entities that do not belong to a group could be aggregated together in a 'remainder' group to simplify this process, though a practitioner should be explicit about that choice.

3.3.3 Example

We show results for process group CA in Fig. 4. The grouping is done based on four tagged categories, which are also color-coded for clarity. As shown, the groupings are based on tags for 'resources extraction', 'energy production', 'manufacturing', and 'use'. It is still possible for the groups to have no impact (e.g. 'use'). The results are shown in Fig. 3D in context with other approaches.

3.4 Advantages and limitations of the direct approaches

The three levels (1: individual flow CA, 2: EF/process CA, and 3: EF/process group CA) have a few different tradeoffs between each other based on the level of disaggregation they provide. Where individual flow CA gives the highest level of resolution available, the number of results generated may quickly become too much for effective interpretation with larger systems than this simplified case study. The contribution matrix in Fig. 2B has 12 entries, two for each process. If two EFs and two processes were added, this would become 32, already well over double the amount. Modern databases like ecoinvent (Wernet et al. 2016) have ~5000 EFs and ~20,000 processes. While the vast majority of these entries would be zero, the number of results would still be sizeable.

With all these approaches, due to the potential number of results, many results would likely only contribute a small fraction of the total. Sorting the contributions by magnitude and applying a cut-off to show only the most impactful contributors may help to provide insight.

A major downside of the direct approaches is that the results may in some cases be counter-intuitive, trivial, or not

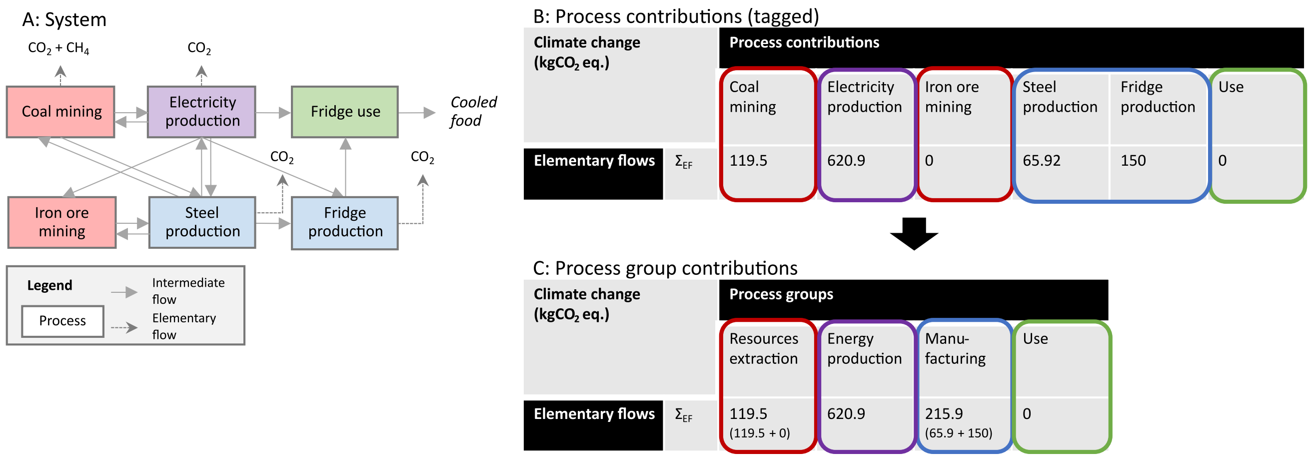


Fig. 4 **A** Overview of the system for the production of 'cooled food' with four groups: 'resource extraction' in red, 'energy production' in purple, 'manufacturing' in blue, and 'use' in green. **B** Process contributions, marked with the groups. **C** Process group contributions, showing the contributions *from* process groups *to* characterized results

helpful. An example of a counter-intuitive result is that, while the use process of the fridge is naively considered to be the major contributor *to* climate change, the tables in Fig. 2B–D show that its *direct* contribution to climate change is zero. The 'fridge problem'—where one would intuitively expect the use of the fridge to be responsible for part of the contribution—was first introduced by Heijungs and Kleijn (2001) and is caused by the fact that these direct approaches only show *direct* contributions. This problem of assigning *indirect* contributions cannot be resolved by direct approaches to contribution analysis. Similar to the 'fridge problem', an example of a trivial result would be to find that the only contributor to 'resource extraction' is a mining process, though this again comes down to the same question of *indirect* contributions; we show a triviality example in Table SI 12 in SI 1.3.1. While the mining processes *directly* contribute to resource extraction, other processes require those resources. In the following chapters, we discuss different approaches that can answer questions from this *indirect* perspective.

Finally, there is a specific challenge to the grouping approaches: These approaches require more input from the practitioner by defining groups; attention needs to be paid to double-counting or dropping flows. These groups need to be clearly defined, and if a 'remainder' is used, this needs to be communicated clearly. Modern LCA software can help with grouping, for example based on metadata present in modern LCA databases.

4 First-tier contribution analysis

4.1 Goal

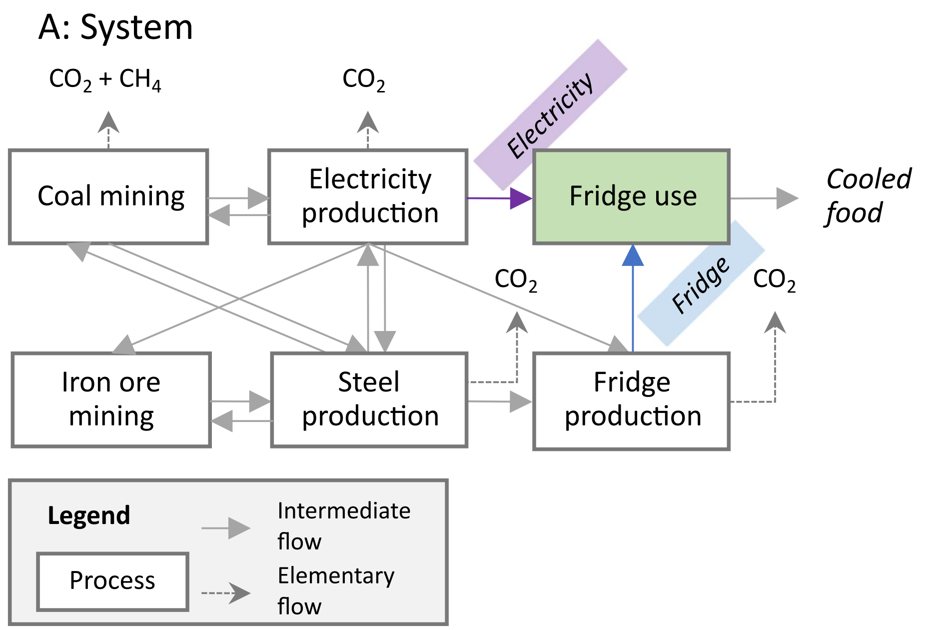
First-tier contributions (sometimes also called product contributions, first-level, first-order, or n-1 contributions) are the contributions *from* the (intermediate and elementary) flows required in the process delivering the FU.

The goal of first-tier CA is to find the contributions *from* the intermediate flows (products) consumed and *direct* EFs emitted by the process providing the FU; this is an *indirect* perspective. A practitioner could use first-tier CA to investigate the contributions *from* 'electricity' on the fridge use. This would, in contrast to the process contributions for electricity production, include all *indirect* contributions related to the production of electricity as a product (e.g. the coal burned for electricity production and the steel produced for the power plant). Another example could be a manufacturer wishing to find the impact of components (compressor, insulation, frame, etc.) used in the fridges they produce.

4.2 Description

This approach is fundamentally different from the direct approaches as these results cannot be calculated from the contribution matrix. Instead, this approach makes use of partial-LCA: Partial-LCA splits the FU into different partial-FUs, with all parts combined still accounting for the original FU. Partial-LCA allows practitioners to assess the contributions *from* each of these partial-LCAs.

In first-tier CA, the FU is split into one partial-FU for the process delivering the original FU one for each intermediate



B: One FU to Partial-FUs

	Cooled food
Coal	0
Electricity	0
Iron ore	0
Steel	0
Fridge	0
Cooled food	8

	Elect-ricity	Fridge	Fridge Use
Coal	0	0	0
Electricity	600 (8*75)	0	-600 (8*-75)
Iron ore	0	0	0
Steel	0	0	0
Fridge	0	1 (8*0.125)	-1 (8*-0.125)
Cooled food	0	0	8

C: First-Tier contributions

Climate change (kgCO_2 eq.)		First-tier contributions		
		Electricity	Fridge	Fridge use
Elementary flows	Σ_{EF}	574.6	381.74	0

Fig. 5 **A** Overview of the system for the production of 'cooled food' with first tier marked: The process 'fridge use' in green, and the intermediate flows 'electricity' in purple and 'fridge' in blue. **B** Full functional unit (FU) and partial FUs, split for the original process and each of the intermediate flows. **C** First-tier contributions, showing the contributions *from* the first-tier (*direct* contribution from the process 'fridge use' and *indirect* contributions from the intermediate flows 'electricity' and 'fridge') *to* characterized results

flow into that process. First-tier CA can only be applied to FUs where exactly one product or service is consumed. The first partial-FU delivers the original FU minus all intermediate flows connected to the process of the FU. All partial-FUs are scaled to the amount required for the original FU. We show this in Fig. 5A and B; in SI 1.4, we explain and demonstrate partial-LCA for first-tier ca in more detail.

As an example, the contributions of ‘electricity’ for the fridge use would be found by calculating the partial-LCA result for the intermediate flow of ($75\frac{kWh}{year} * 8year$) 600 kWh electricity (as derived from the electricity input for the use process in Table 1).

The first-tier results show the *direct* contribution *from* the process delivering the original FU and the *indirect* contributions *from* the intermediate flows consumed by that process.

4.3 Example

We show the results in Fig. 5C. We also show the comparative results in Fig. 3E. Note that the contribution from ‘electricity’ in Fig. 5C is higher than the process contribution impact of ‘electricity production’ in Fig. 2D; these values differ, as first-tier contributions *from* ‘electricity’ show the contribution of not only ‘electricity production’ (for 600kWh), but also other *indirect* impacts from other processes required to produce that electricity. Also note that we include ‘direct EF’ in Fig. 3E representing the ‘use’ process, though the contribution is zero.

4.4 Advantages and limitations

There are three major advantages to this approach. First, the number of results is reduced to the number of intermediate flows of the process delivering the FU plus one for the *direct* EF contributions, which aids in interpretation. Second, the approach partially solves the problem of trivial results. For example, the contributions to ‘mineral extraction’ would now be shown not *from* the mining process, but as a part of the impact of the intermediate flows of the process delivering the FU; we demonstrate this in SI 1.4. Third, as full LCA calculations are used on each of the partial-FUs, other CA approaches may be applied to the partial-LCAs; we discuss this further in Sect. 5.3.3.

There are a few disadvantages to this approach. Despite the results being non-trivial, a substantial amount of information is removed from the results. As only the contribution from the first level is counted, this approach cannot provide deeper insight into the source of the contributions of the inputs. Finally, this approach can only be applied to FUs consisting of one product or service, though this approach could be applied sequentially to resolve this. A FU consisting of multiple products, for example a multi-functional process “basket of functions” (Majeau-Bettez et al. 2014), could be assessed sequentially for every function.

5 Life cycle stage contribution analysis

5.1 Goal

Contribution analysis *from* life cycle stages shows the contributions of different life cycle stages. For this study, we define a life cycle stage as an interdependent sequence of one or more processes connected by their intermediate flows and producing a functional flow. What processes are part of which life cycle stage should be chosen by a practitioner as useful units of enquiry for a specific question they want to answer. Life cycle stages can be connected through consuming the functional flows of other life cycle stages. Not all processes need to be assigned to a life cycle stage, as the underlying product system does not change; the un-assigned processes will contribute to the life cycle stages indirectly. Figure 6A shows three examples of life cycle stages. Note that in this simplified example, ‘electricity production’ and ‘coal mining’ are not part of a life cycle stage, but will still indirectly contribute to all of the life cycle stages. Two other examples from this system could be a stage of the two processes ‘iron ore mining’ and ‘steel production’ called ‘steel’, or one consisting of the two processes ‘coal mining’ and ‘electricity production’ called ‘energy’. In general, useful life cycle stages may be ‘production’, ‘use’, and ‘end of life’, with relevant processes chosen by the practitioner. Note that, although life cycle stages and their contributions are a cornerstone of the Product Environmental Footprint (PEF) method (European Commission, 2013; Zampori & Pant 2019), the guidelines provide examples of life cycle stages but never explicitly define or formalize the concept.

The goal of this approach is to find contributions *from* individual life cycle stages. A practitioner could use life cycle stage CA to assess the contributions of various -practitioner defined- stages of production, e.g. contributions *from* a ‘materials production’ stage. This approach can be useful to find contributions for life cycle stages along a supply chain a manufacturer has control over.

We discuss two different approaches to life cycle stage CA: process groups and partial-LCA. Both approaches require careful input from the practitioner to define and communicate the life cycle stages.

5.2 Group life cycle stages

5.2.1 Description

Group life cycle stage CA is based on the direct process grouping approach by tagging processes to life cycle

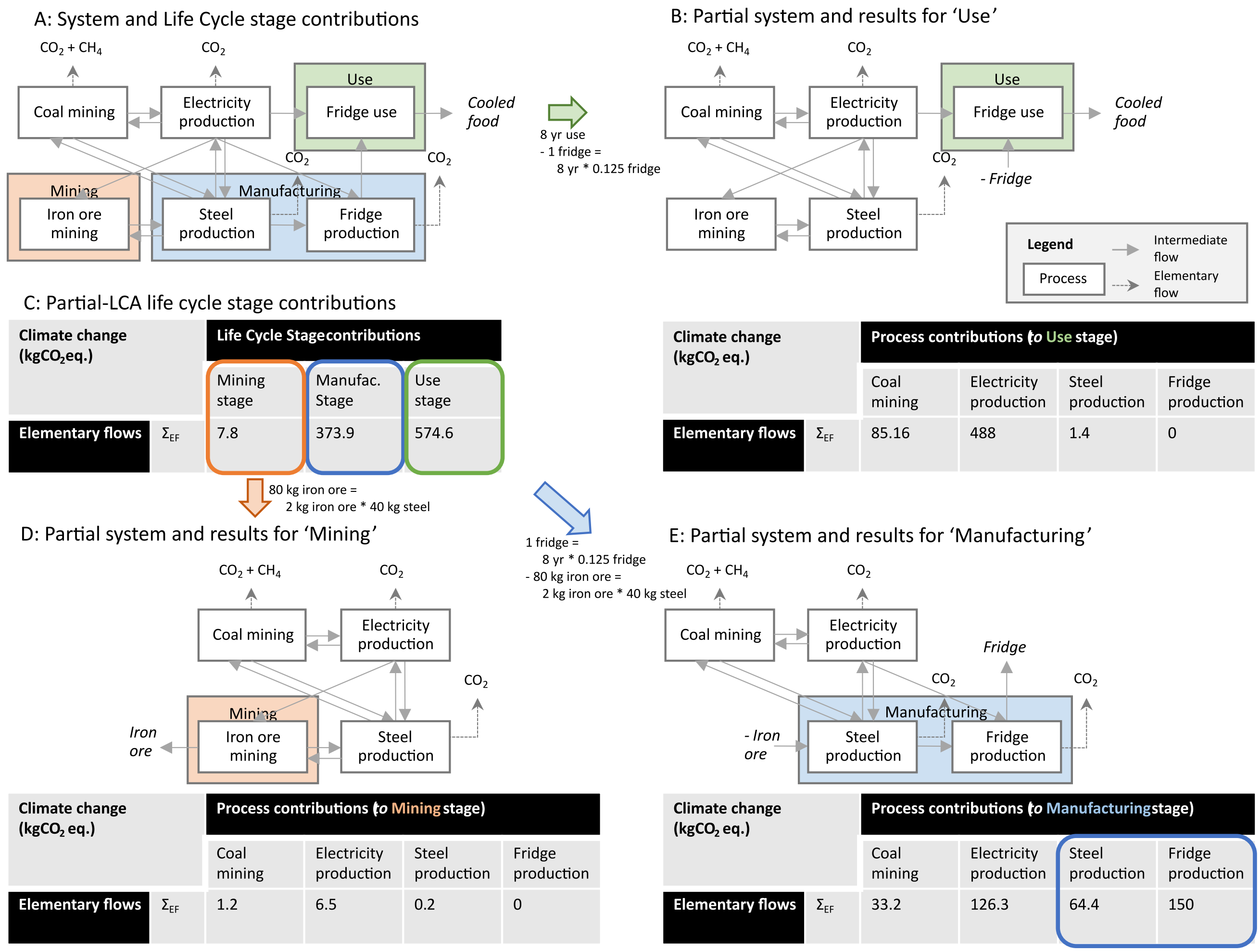


Fig. 6 **A** Overview of the system for the production of 'cooled food' with three life cycle stages: 'mining' in orange, 'manufacturing' in blue, and 'use' in green. **B** Partial system for life cycle stage 'use' and process contributions *to* 'use stage' characterized results. **C** Partial-LCA life cycle stage contributions, showing contributions *from* life cycle stages *to* characterized results. **D** Partial system for life cycle stage 'mining' and process contributions *to* 'mining stage' characterized results. **E** Partial system for life cycle stage 'manufacturing' and process contributions *to* 'manufacturing stage' characterized results. Also showing grouped process contributions *from* processes in the stage marked in blue

stages and—if required—creating a 'remainder' group, as described in Sect. 3.3.2. As this approach is a specialized use of process group CA, it carries the same advantages and disadvantages; most relevant here is that this approach can only show *direct* contributions. To use the example of Fig. 6A and the life cycle stages defined above, the upstream processes of 'electricity production' and 'coal mining' would both (indirectly) contribute to all life cycle stages and, as such, could not be 'tagged' into a life cycle stage and are part of a 'remainder' group.

5.2.2 Example

We show this result in Fig. 3F. As can be seen, the majority of the contribution comes from the 'remainder' group, with the *direct* contributions of the life cycle stages being low or zero.

5.2.3 Advantages and limitations

While grouped life cycle stages may be able to reduce the number of results, this approach has the same limitations as discussed in Sect. 3.4; most importantly, the approach cannot show *indirect* contributions, i.e. the 'fridge problem'.

5.3 Partial-LCA life cycle stages

5.3.1 Description

Partial-LCA life cycle stage contribution analysis applies partial-LCA to calculate contributions of different life cycle stages; this allows to find both *direct* and *indirect* contributions *from* life cycle stages. Contrasting with first-tier CA from Sect. 4.2, though, the partial-FUs are used to differentiate life cycle stages throughout the product system. A way of transforming life cycle stages into partial-FUs is with 'modular LCA' as formalized by Steubing et al. (2016). The splitting of the original FU (into one FU for every life cycle stage) enables the life cycle stages to be calculated. In this simplified example, the life cycle stage 'manufacturing stage' would produce 1 fridge and consume 80 kg iron ore from 'mining stage'. More iron ore is required in the system for steel in other end-uses, but this is not considered directly in this life cycle stage, though it is considered for the total impact. We explain and demonstrate partial-LCA life cycle stage contribution analysis in SI 1.5. As partial-LCA is applied, the contributions *from* each life cycle stage sum to the total impact.

5.3.2 Example

The results of a partial-LCA life cycle stage contribution analysis show the contribution *from* each life cycle stage. We show an example of the three life cycle stages 'mining', 'manufacturing', and 'use' for the simplified fridge product system in Fig. 6A. We also show how the results compare to those of the other CA approaches in Fig. 3G. Depending on the question of the practitioner, these results may provide more insight into the life cycle stages compared to group-based results shown in Fig. 3F.

In the simplified example, the resulting contributions *from* each of the three life cycle stages are shown in Fig. 6C. Important to note here is that the 'use' life cycle stage is responsible for the majority of the total impact through its *indirect* contribution, while its *direct* contribution is 0. A part of the *direct* contribution *from* 'coal mining' and 'electricity production' is now associated with each of the life cycle stages. This is another way of applying partial-LCA to solve the 'fridge problem'.

5.4 Advantages and limitations

The main advantage of this approach compared to the previous ones is that not only can it reduce the amount of results, it can reduce complexity in interpreting the results of an LCA—especially when large databases are used—as the contributions from only a few life cycle stages need to be considered compared to the contributions from many processes, EFs, or groups; we discuss this further in SI 1.7.

As partial-LCA is applied to calculate results, an important implication for this approach is that other CA approaches can be applied *to* the partial results, which allows for deeper insights into the system studied. We show this for process contributions *to* the life cycle stages in Fig. 3H and Fig. 6B, D, and E. We also apply process grouping to differentiate between *direct* and *indirect* contributions in Fig. 6E. We discuss this use of other CA approaches *to* partial-LCA results further in SI 1.5. Finally, life cycle stage contributions can also be grouped; we demonstrate this in SI 1.5.3.

The major downside of this approach is that it requires more modelling effort from the practitioner, who needs to define life cycle stages and the functional flows of the processes that need to be cut-off between life cycle stages, as further described in SI 1.5.

6 Path contribution analysis

6.1 Goal

Following from first-tier CA, a practitioner may want to investigate the first-tier contributions for another intermediate flow (e.g. what are the first-tier contributors for the fridge?), expanding this first tier to paths of contributions. Results from this type of approach are often shown in a Sankey diagram (Sankey 1898).

The goal of path CA is to find how contributions *from* intermediate flows throughout the product system lead to the final LCA score. A practitioner could use path CA to investigate through what intermediate flows (e.g. products) the production of electricity *indirectly* contributes to the final impact. Another example could be to find which components and sub-components of a fridge may be responsible for what *indirect* contributions.

6.2 Description

This approach shows the contributions *from* intermediate flows between processes. Path CA makes use of the networked structure of product systems which can be traversed and considers the contribution at any intermediate flow the product system, scaled to the FU. As the contributions are not *to* the FU but instead *to* any intermediate flow in the system, the contributions do not add up to the total LCA result. For this reason, this approach should not be considered contribution analysis in the strict sense, though this fact does not diminish its widespread use and practical usefulness to assess contributions, which is why we still discuss this approach.

While Sankey diagrams have been used abundantly in reporting contribution results in LCA, to our knowledge, this approach was only formalized for inventory results recently by Srocka and Montiel (2021), who call this 'upstream contributions'. However, we do not agree with this naming as contributions could also be counted from 'downstream' processes, e.g. with waste treatment. The approach by Srocka and Montiel (2021) calculates the path contributions for all intermediate flows in the system at once; we demonstrate the approach in SI 1.6, also for characterized results. The path contributions can also be calculated for (a part of) the product system iteratively, which can be more efficient for large systems.

6.3 Example

We show a Sankey diagram of the simplified case study in Fig. 7. The figure shows the path contributions through the system. Caution must be paid in the interpretation of the figure: While the path contributions (lines connecting the boxes) are shown as a percentage of the total impact, they should not be summed, as explained earlier.

6.4 Advantages and limitations

Path CA has two advantages. First, it can show contributions throughout the product system. This can help identify key processes and intermediate flows that affect results highly. Such processes could have a low (or no) *direct* contribution themselves, but instead have a 'connector' role (Reinhard et al. 2019), 'accumulating' contributions through their intermediate flows. Secondly, path CA can also answer questions regarding the responsibility for *indirect* contributions. For example, in Fig. 7, we show that 'electricity' does not only have the biggest contribution *to* 'use' but also *to* 'fridge production', where the *indirect* contribution *from* 'electricity' is higher than the *direct* contribution of the process itself.

There are also some strong limitations to this approach: Firstly, graphical representation is complex, due to the fact that the LCA results do not add up to the total impact (double counting, as explained in SI 1.6.1); these results should not be shown in traditional graphs like bar charts. The results can be shown through a Sankey diagram or a tree structure. However, these can make it harder to compare alternatives to each other. Another limitation is that the approach is limited to a FU of one product, like first-tier contributions. Additionally, Srocka and Montiel (2021) identify an additional limitation to their approach: Open loops—i.e. loops including the FU—cannot be computed. The iterative approach has the advantage that a cut-off can be applied, thus limiting the number of results.

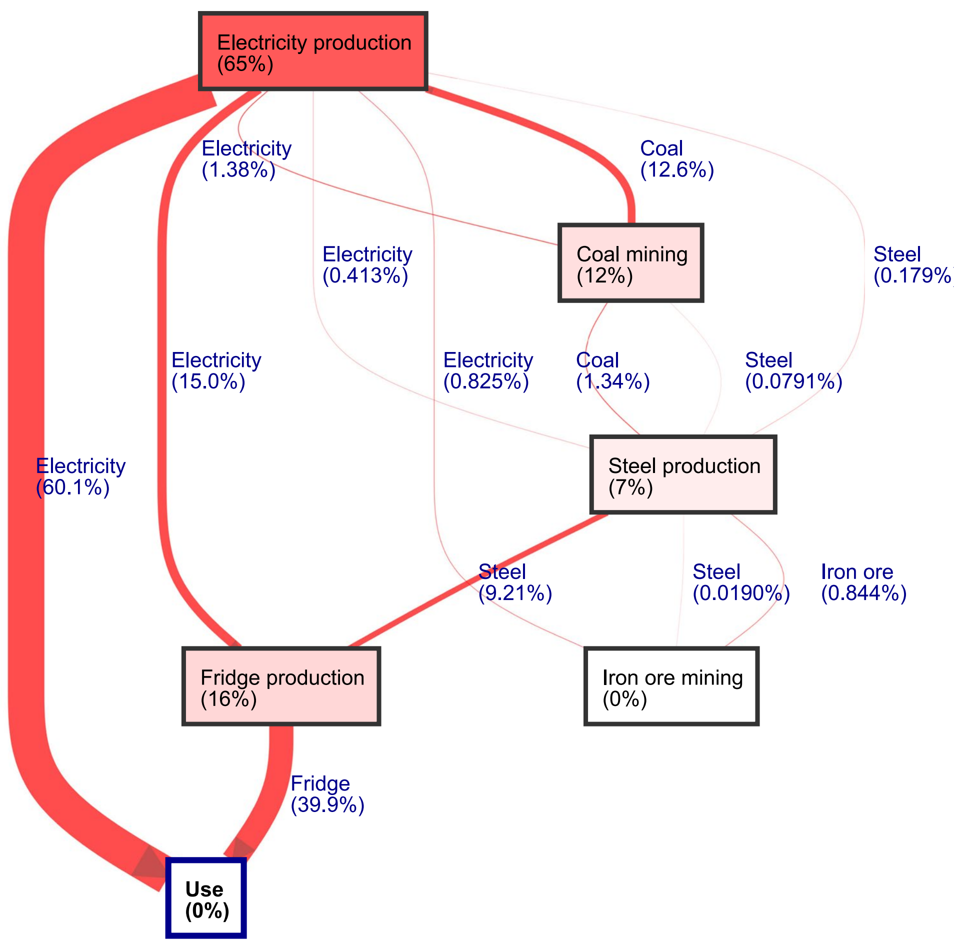


Fig. 7 Sankey figure of the path contributions for the production of 'cooled food'. Each box represents a process, each line an intermediate flow between processes. The percentages for processes are the relative *direct* contributions. The percentages for the intermediate flows are the relative *indirect* path contributions at these intermediate flows

6.5 Similar approaches to path contribution analysis

Two similar approaches to path CA are from Reinhard et al. (2019), who demonstrate a similar concept with the 'connector perspective', though they applied this to every product in the product system at once, instead of to a singular FU, limiting use in normal practice. The other is contribution trees in Srocka and Montiel (2021, Sec. 7.4.3), where contributions are shown in a tree instead of a network. We discuss the difference between path contributions and contribution trees in SI 1.6.2.

Other similar approaches to path CA are structural path analysis (Suh & Heijungs 2007; Waugh 1950), path exchange method (Lenzen & Crawford 2009) and output contributions (Suh, 2004). However, these approaches are mainly limited to IO-LCA and can be challenging or impossible to apply to process-LCA (Heijungs et al. 2022; Suh & Heijungs 2007). We refer to Heijungs and Suh (2002), Lenzen and Crawford (2009), Suh and Heijungs (2007), and Suh (2004) for further discussion of these approaches.

7 Discussion

7.1 Contribution analysis to other entities

So far, we only discussed contribution analysis *to* characterized results (or partial characterized results), as this is most commonly shown in literature. CA can, and has been, applied to other entities as well. In Table 2, we give an overview *to* which entities each CA approach we discussed is compatible with.

For the life cycle inventory, CA cannot be applied *from* processes or process groups, as the EFs in those processes cannot be combined without characterizing them (combining 'kg CO_2' and 'm^2 of land use' is not possible without characterizing the EFs).

As partial-LCA results have the same format as 'regular' LCA results—just for each partial FU—each of the approaches could also be applied *to* partial-LCA, keeping in mind the limitations of those approaches. As an example, it could be useful to apply process CA *to* the partial-LCA life cycle 'manufacturing' (as shown in Fig. 3H). Conversely, partial-LCA results can also be grouped, e.g. first-tier contributions grouped into 'materials', 'energy', and 'transport'.

For normalization and weighting, the same approaches can be used as *to* characterized results. Though the contributions *from* characterized results *to* normalization and *to* weighting could also be applied. Finally, *from* normalized results *to* weighted results could be used.

7.2 Comparison of CA approaches and their domain of application

As demonstrated in Figs. 3 and 7, each approach to CA provides different results and insights by assessing the same system from different perspectives. While the direct approaches use the same information, first-tier, partial LCA life cycle stage analysis, and path contributions require additional calculations to provide results.

The approaches we demonstrated above vary in the resolution of results they can give. In Table 3, we provide an overview of key aspects to each of the approaches. Because LCA results may provide a large amount of information, having high resolution is not always advantageous. The individual flow, process, and EF CA approaches are best applied

Table 2 Overview of the CA approaches: from approach (rows) to entity (columns). Grey cells show that an approach can be applied to that entity. Where relevant, we refer to the section and figure where the approach to that entity is discussed in the cell

From \ *To*	Life Cycle Inventory (EF)	Characterized result	Normalized result	Weighted result
Individual flow	SI 1.3.1	Sec. 3.1 / Fig. 2B		
EF	SI 1.3.2	Sec. 3.2 / Fig. 2C		
Process		Sec. 3.2 / Fig. 2D		
EF group		SI 1.3.3		
Process group		Sec. 3.3 / Fig. 4B		
First-Tier	SI 1.4	Ch. 4 / Fig. 5C		
Life Cycle stage		Ch. 5 / Fig. 6		
Path	SI 1.6	Ch. 6 / Fig. 7		
Partial-LCA group		SI 1.5.3		
Characterized result				
Normalized result				

Table 3 Comparison of key aspects of CA approaches *to* characterized results. The columns show key aspects: example research questions, examples, resolution of results (how detailed are the results?), perspective (can the approach show *direct*, *indirect*, or both perspectives?), and finally potential challenges for interpretation and additional inputs needed from a practitioner

		Example research question	**Examples (*to* characterized results)**	**Resolution**	**Interpretation challenges and additional inputs**
Directapproaches	Individual flows	Which individual EFs from which processes contribute how much?	- Top contributions *from* individual EF caused by a process	Highest	- Amount of contributions, can be reduced by sorting and cut-off - Direct contributions only: the 'fridge problem'
	Elementary flow (EF)	Which EFs contribute how much?	- Top contributions *from* EFs	High	
	process	Which processes contribute how much?	- Top contributions *from* processes		
	EF group	Which EF groups contribute how much?	- Contribution *from* all carbon-containing flows	Depends on group size	- Requires definition of groups (could automated through meta-data). Any 'remainder' groups must be made clear - Amount of contributions, can be reduced by sorting and cut-off - Direct contributions only: the 'fridge problem'
	Process group	Which process groups contribute how much?	- Total contribution *from* electricity inputs - Contribution *from* specific ISIC sector		
Direct + indirectapproaches	First-tier	Which intermediate flows and EFs contribute how much?	- Contributions *from* inputs-to and production-of a fridge	Low	- First tier inputs do not give insight into deeper sources of contributions than the first tier
	Life cycle stage	Which life cycle stage contributes how much?	- Life cycle contributions *from* each stage	Depends of life cycle stage amount	- Requires definition of life cycle stages and how they connect
	Path	Which intermediate flows form paths of major contributions?	- Intermediate flows that contribute to final result	Depends on cut-off	- Does not necessarily show the entire system or full impacts. Loops and FUs consisting of multiple processes may form interpretation challenges

when looking for contributions from specific entities, with cut-offs applied to reduce the number of results, or when working with small systems. The grouping, first-tier, life cycle stages, and path approaches are primarily useful with larger systems, where they can be effectively used to reduce the amount of information; we show this with an example using the ecoinvent database (Wernet et al. 2016) in SI 1.7. While partial-LCA life cycle stage CA requires more input from the practitioner compared to the other approaches due to the definition of life cycle stages for their system, we see this approach as a particularly useful approach to provide actionable results. We also note that with larger systems, most, if not all, approaches would benefit from additional input, mostly in the form of cut-offs or groupings to reduce the amount of results. Each of the approaches can be useful, and the practitioner should choose which are most relevant to the questions they want to answer.

Another main difference is whether the approach shows only *direct* results or also *indirect* results. A notable example is the difference between Fig. 3C and E. If we consider 'electricity production' (a process) and 'electricity' (an intermediate flow), these may at first sight be considered the same, but the former shows the *direct* contribution of the process, while the latter show the *indirect* contribution of the product. This means the impacts will be different. On the one hand, the contribution of 'electricity' is increased as it includes contributions from other processes (e.g. 'coal mining'); on the other hand, the contribution is decreased as not all electricity is consumed by 'use'; some is also used by other processes (e.g. 'fridge production'). The net effect of both is a higher impact compared to 'electricity production' in this simplified example, but this will depend on the case.

Partial-LCA life cycle stage CA is a required method by the PEF method (European Commission, 2013; Zampori & Pant 2019). In the PEF, 'raw material acquisition', 'manufacturing', 'distribution', 'use', and 'end of life' are required as life cycle stages for which contributions must be reported. Building further on this, EN 15804 + A2 (2019) introduces even more sub-modules. These could be calculated as individual life cycle stages, after which the life cycle stage results could be grouped into the full modules, as we demonstrate in SI 1.5.3. Another use of grouping of life cycle stages is the application of the scopes (1: direct, 2: indirect from electricity, 3: all other) from the GHG Protocol (2004) and ISO 14064 (2018), as we discuss in SI 1.5.3.

Finally, we mention some other notable approaches of CA we have not discussed in more detail: The identification of processes in the ecoinvent database (Wernet et al. 2016) that contribute highly to many different impact categories through differentiating between *direct* contribution and *indirect* contribution perspectives (Reinhard et al. (2019), who name this causer and connector perspective, respectively). Identifying the importance of capital goods in the ecoinvent database (Frischknecht et al. 2007). The analysis of abiotic resources in the ecoinvent database (Rørbech et al. 2014). These approaches can also be useful to practitioners in specific cases, though their use is not common in literature.

7.3 Limitations to contribution analysis

While one of the most important limitations to CA was summarized as the 'fridge problem' (trivial or counter-intuitive results) introduced by Heijungs and Kleijn (2001), we have shown that this is only a limitation of CA approaches that show *direct* results. This limitation can be resolved by using approaches that show *indirect* results as well.

There are still three major limitations to all discussed approaches to CA that should be taken into account when using any approach: the use of negative numbers, missing data, and the verifiability of results.

Firstly, the occurrence of negative numbers in LCA results (Heijungs & Kleijn 2001). Note that here we discuss numbers below 0; this does not imply anything about the desirability of that result. Negative numbers can occur in various cases: negative elementary flows (e.g. CO_2 uptake in forestry), negative characterization factors (e.g. atmospheric SO_2 as a decreasing global warming effect), or negative intermediate flows due to substituted processes (avoided production). Negative numbers void the use of pie charts and can make it more difficult to interpret results effectively, especially with relative representations. We discuss some examples and approaches to present negative numbers in SI 1.8.

Secondly, Heijungs and Kleijn (2001) also point toward the limitation of missing data; contribution analysis can only show contributions of what is modeled. While this limitation may seem obvious, this limitation is especially relevant in two cases: (1) when using CA as input for sensitivity analysis or (2) when using CA in early project phases when there are still data gaps or detailed data may not be available.

While Heijungs and Kleijn (2001) only discussed the direct approaches to contribution analysis, these limitations are still important for all approaches we have discussed here.

Finally, when performing LCA, it is important to be able to verify that results are correct and the calculations are performed correctly. We suggest practitioners—especially academics—make use of software that allows users to inspect the algorithms such that they can be verified to provide correct results.

7.4 Reporting contribution analysis

In reporting CA, we recommend reporting the following points to ensure the CA is better replicable and useful for the study it is applied in:

- What approach is used and *to* what entity it is applied,
- Additional information relevant to the approach:
  - o Cut-offs if any,
  - o What EFs/processes are in groups and if a remainder is used,
  - o Processes in life cycle stages and the functional flow of those stages
  - o The specific software or tool—and version—used, as implementations may vary with different tools,
- How the chosen approach helps answer their research question,
- Results should be available in tabular form (either in main text or appendices),
  - o Results can optionally be reported in a graph, e.g. a stacked bar chart like Fig. 3.

Some examples are as follows:

- 'We use EF Group Contribution Analysis *to* LCI results to investigate carbon containing EFs in Excel (provided in SI x), all other EF are grouped as 'rest''.
- 'This study applies Process Contribution Analysis to find major contributing processes *to* 'resource extraction' with a cut-off of 5% contribution, the resulting processes are used in sensitivity analysis in software x version y.'
- 'First-Tier Contribution Analysis is used to find the 'climate change' impact *from* components in a fridge with python (code provided in SI x) to inform supplier choices.'

As demonstrated in the examples above, describing a CA approach does not require much space in a report or manuscript, but providing this description can considerably improve clarity and replicability for readers about what the practitioner has done.

Finally, CA is sometimes applied in combination with sensitivity/uncertainty analysis. When this is the case, contributions of individual entities may change through different calculations, which may be relevant to report as well. We note here that this would not be possible in the stacked bar chart we use in Fig. 3, as uncertainty ranges could not be combined as such, though each contributing entity may be shown as an individual bar with an uncertainty marker. This is discussed in more detail in Heijungs (2024).

8 Conclusion

With this study, we set out to structure, explain, and provide a clear terminology for different CA approaches. We introduced the *from-to* relationship, classified different approaches based on the *from*, and discussed *to* what they can be applied. Furthermore, we also make a distinction between the *direct* and *indirect* perspectives on contributions and how these perspectives help answer different questions. Through discussing each approach with its goal, workings, advantages, and disadvantages as well as comparing the results of each approach to the same simplified case study, we have shown the different insights each approach can provide and in what cases which approach may be most useful. Additionally, we formalized the use of partial-LCA for first-tier CA and life cycle stage CA, and expanded on the use of path CA for LCIA results.

As we have shown with this overview, each of the approaches has its place in the toolbox of the LCA practitioner and can be used to provide different insights into LCA results. Which approach is best applicable is best judged on the question that needs to be answered. Applying multiple approaches is recommended to gain deeper insight and complementary perspectives on results. This study can help those new to LCA, as well as experienced practitioners and LCA software developers to gain deeper insight into these approaches, especially by referring to SI 1 and SI 2 where each approach is presented in more detail and calculations are presented.

Through applying the right CA approach for the question and case at hand, we hope practitioners can gain better insights and more transparently communicate and report their results. This should contribute to a higher quality and more reproducible body of LCA literature and more well-founded conclusions.

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Data availability All data used in this study is available in SI 1 and SI 2.

Declarations

Competing interests The authors declare no competing interests.

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