Disclosure of product system models in life cycle assessment: achieving transparency and privacy

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# Response to Reviewers

I offer many thanks to the anonymous reviewers for their close review of my manuscript. Based in part on their recommendations I have significantly revised the manuscript. Every section after the introduction has been either reworked or newly created. I have narrowed the scope to concentrate on structured representation of product system models, and to exclude many aspects of publishing those models that were present in the first draft. With this narrowing of scope I have been able to add new focus areas on private or confidential information in the model and on implications for critical review, both of which were highlighted by Reviewer #3. I have also thoroughly revised the mathematical development to be clearer and more precise in accordance with the suggestions from reviewer #1, which were highly appropriate, and I hope that the reviewer can now make it to the end of the text. The comments from Reviewer #2 were immeasurably helpful in identifying weaknesses and ambiguities of the prior version.

Below I respond to the reviewers' comments individually. Page numbers refer to the native pagination (centered numbers in footer) in the revised manuscript.

# Reviewer #1

This is a potentially important paper, and it may have a great influence on the - usually poor - reporting of case studies. However, the paper suffers from quite a few flaws, mostly mathematical. Through this, I stopped reading at some point, and first ask the author to make his work better understandable. I am happy to have a closer look after that.

In general, the mathematics has been cleaned up extensively, and I adopted almost all of the reviewer's suggestions. The notation should be self-consistent throughout the manuscript (though not, unfortunately, consistent with Heijungs and Suh) and all symbols are properly introduced and defined. The supplementary information also includes proofs or derivations for all equations for which this is necessary. Finally, I have attempted to introduce the "canonical" LCA foreground study (p. 10 top) in a way that is both easy to understand and useful for the development. The comments were very helpful (and in some cases, such as in observing my misuse of the cross product notation, a bit embarrassing). I believe the mathematical development has been greatly strengthened in the revision, and I hope the changes make the manuscript more intelligible to the reviewer and ultimately to readers.

1. Dependency and ordering. Page 5, line 54 states that foreground processes are dependent on background processes but not the other way around. Hance the processes can be partially ordered. The validity of these statements depend on the meaning of the word "dependent"....

Thank you for this observation. In the revised manuscript I have emphasized that "dependent on x" means "x is required to perform the LCA computation." In this sense, the foreground of the study depends on the background but not vice-versa. This is explained at p.8.

... Another example is the so-called integrated hybrid IOA-LCA, where all quadrants contain non-zero cells.

I added discussion of integrated hybrid models to the section on LCA foreground studies, p. 10 top.

2. Most equations contain a cross (x) for matrix and vector multiplication. Please do not…

Thank you for pointing out this error. I have corrected the notation.

3. Why do you start using "classic formulation ... Heijungs & Suh", but use different symbols (y for f, s for h), which are moreover confusing (because s means something different to Heijungs & Suh).

I have removed the reference to Heijungs and Suh's notation.

4. The notation in eq (1) has y as a column vector and e as a row vector. It would be better to adopt one convention (please make it column vectors), and write a row vector with a transpose symbol...

I have done as the reviewer suggests, both in the text and in the figures.

5. What is the reason of rewriting eq (1) into eq (2)? As I see it, it only complicates, because every appearance of "A^-1" now reads "(I-A')^-1"....

Reviewer #2 also commented on this confusing aspect. I have adopted the input-output notation exclusively in the revision, because it is more convenient to represent the ordering in terms of a normalized adjacency graph than a technology matrix. The complication to which the reviewer objects is no longer present, because I no longer introduce the "classical" technology matrix formulation at all.

Comments 6-11 are not applicable in the revision because of notation changes and editing.

12. Page 7, line 49 until page 9, line 4, "The following formulation is equivalent to Eq. 3: ... where Bx=B\*..." Please supply a proof (you may use an appendix for that).

13. Similar for page 9, line 6: "Eq. 2 can be written ...", this needs a proof.

Comments 12-13: proofs have been provided in the supplementary materials for both these relations, which are between equations 3 and 4, and equations 1 and 5 respectively in the new manuscript.

Comments 14-17 and 19 have also been accounted for through improved notation.

In these passages, I have used the tilde modifier to represent any LCI database that is made up of a background database augmented with foreground content and appropriately ordered so that the foreground is to the left / above the background. The "canonical" functional unit is now the functional unit that selects a unit output of the first column of the technology matrix. The x-tilde, y-tilde, and y\_f vectors are defined explicitly, beginning at the top of p.10 (y-tilde), on the bottom of p. 10 (y\_f), and top of p.11 (x-tilde).

Comment 18 ... states that the foreground needs no matrix inversion, because you can "traverse the graph". Can you specify concrete formulas...

The passage has been removed. However, the equivalency is quite interesting. There is a useful treatment of a related problem in Bapat and Ghorbani, 2014 in *Linear Algebra and Applications* (DOI: 10.1016/j.laa.2013.03.002), hereafter BG14. It is not easy to make the analogy because technology matrices, though derivable from bipartite graphs, are not themselves bipartite. The bipartite graph in BG14 theorem 1 essentially can be imagined to correspond to an LCI database in supply/use form, and the adjacency matrix A in BG14 theorem 1 is the normalized technology matrix that is derived from the supply and use matrices.

The traversal process cannot be stated easily as concrete formulas because it is essentially algorithmic (the proof in BG14 is by induction). But the algorithm is the same as what is used to iteratively compute the matrix inverse from the direct requirements matrix. Sequential multiplications of a unit demand vector by the technology matrix represent sequential steps in a traversal of the graph. Every nonzero value in the resulting multiplication will be the product of the exchange values that have been traversed, i.e. the node weight of the node that has been arrived at in the traversal. If this matrix is sparse and acyclic (lower-triangular), then the traversal will end after a finite number of multiplications that cannot exceed the rank of the matrix. The sum of these vectors will report the accumulated weights of each node that was traveled through during the traversal, in the same way that the total requirements matrix can be derived by an infinite sum of powers of the direct requirements matrix. But the infinite sum is not required if the graph has no cycles.

Ultimately, the requirement that the foreground has no cycles is overly limiting and not necessary, so I removed it.

# Reviewer #2

"... sound mathematical description and a guideline and examples of how to extract and format crucial LCA results ... well suited for publication in JIE."

Thank you for your constructive review. In my revision I have steered away from the practical implications of sharing models, which are complex and include challenges that I was unable to address in the prior draft, and focused more on the mathematical framework that would allow these challenges to be addressed in the future. Thus the scope of the manuscript has been reduced. One advantage of this is that I could focus more on aspects that relate to the quality of the disclosure-- namely, in discerning how varying levels of transparency can be achieved through different partial aggregation strategies. This also allowed me to strongly consider the implications for critical review, as requested by Reviewer #3.

+ The level of detail at which the results are shared determines the types of analysis that others can perform. When only total background emissions are shared a contribution or structural path analysis is rendered impossible. Next to figure S1 (which is great and should be moved to the main paper), there should be a table listing the types of analysis that can be performed depending on the level of detail at which the results are reported.

I did move the supplemental figure to the main text; however, I did not explicitly list "the types of analysis that can be performed" because I could not imagine making such a list comprehensive. However, in the revision I introduce the concepts of 'review objectives' on p. 4 bottom and 'disclosure constraints' on p.5 top. While I do not explicitly mention structural path analysis, this form of analysis is really not applicable to foreground studies because the 'structural paths' are explicit in the patterns of nonzero entries in the foreground. SPA essentially provides a method for contribution analysis that is important in relatively dense and cyclically dependent input-output networks (as discussed in Peters 2007; DOI: 10.1016/j.ecolmodel.2006.07.041) but largely superfluous in foreground networks of the type described in the manuscript.

Right now, most LCA studies are close to useless when being compared to others because of complete lack of transparency. From that state we have a ladder of improvements to make, and that ladder should be described in detail and linked to the different aggregation steps.

I agree with this assessment. In the revision I emphasize the creation of a "disclosure" in which a portion of the model (up to the entire model) is explicitly reported, while other portions can be held back. The idea is that this, if adopted, will advance the quality of reporting of LCAs and "move us up the ladder".

+ I am missing emphasis on the classification of processes, products, and emissions. Reporting the full names of the data objects (processes, products, elementary flows) is important, but ... we need to provide for unique labelling of data points across databases and computation platforms."

"... version clarity ..."

"... reference products ..."

I agree, the problem of reaching agreement on the meaning of descriptors is quite challenging. The prior version of the manuscript depended on this problem being solved; in the revision, the manuscript is able to elucidate this requirement as an implication of the work without necessarily providing a solution. The discussion section entitled "stable semantic references to study elements" provides an explicit statement of these requirements, and they are also addressed in the Supplementary materials.

+ Throughout the manuscript there is a slight lack of clearness regarding the distinction between flows and coefficients, the difference between the Heijungs and Suh A-matrix and the Leontief-type A-matrix, and the question of which results can be reproduced from which aggregation level or results. More clarity will greatly help the readers less familiar with the computational structure of LCS to grasp the ideas presented here.

I have tried to take this advice to heart in the revision, particularly with the introduction of "Reviewable Private Aggregation" and the new Figure 4.

+ Just a general feeling I had when reading the manuscript: There is a lot of generic description on the importance of metadata.... but I miss the discussion of the real problems ... matching concerns ... to link flows ... automatically to the right background data.... "

Again, I have tried to take this advice to heart, but to some extent I have reduced the scope of the manuscript to exclude some of these concerns. Again the section on "Stable semantic references" is meant to be a call to the community to consider precisely these problems and develop collective solutions.

+ The expected consequences for data providers, data users, database providers, and software developers should be mapped out in more detail. Where are the bottlenecks in setting up this process?

In the revised manuscript, these implications are no longer in scope. The idea of structured disclosure of product system models is directed at modellers and report authors; it will ultimately bear on software makers but that is a matter to be addressed later.

Minor comments:

+ Please also refer to the allocation problem (co-production) and to the crediting problem (material or waste enter different product systems), and cite some relevant literature here.

“Factors such as co-production strategy (Finnveden\_1999, Pelletier\_2014) can also render study findings unreliable or highly contingent.” P. 2

+ P6L13ff: “An LCA study result is ultimately an assertion that, for some input data known as the “model,”…” 1) That describes Attributional LCA, please specify. 2) please rephrase the start of this sentence, as it is unclear how (input) data can be a model.

The comment has been updated to read: "An LCA study result is ultimately an assertion that for some constructed PSM, the delivery of a particular reference flow is associated with a certain amount of environmental impact or potential impact." (p.3 lower) The applicability of the statement is not limited to attributional LCA.

+ P8L40: “generated non-reference outputs (negative values)” Only for some constructs. In the case of partitioning allocation there are no negative inflows as input requirements are split so that only single output process descriptions result.

Noted in a footnote.

+ Equations 3 and 4 are not equivalent. Equ. 4 cannot be used for a structural path analysis, for example, as it contains aggregate information only. Please be more specific.

Updated to read "...equivalency of results derived from Eq.s 3 and 4..."

+ P11L22: “The foreground graph Af can be distilled into a vector of…” please use more scientific language here. A\_f is not a graph but a description of a graph, and distilling reminds me of other things than science…

The passage has been removed.

+ Figure S1 provides a very good summary of the different aggregation steps; consider moving it to the main paper.

Thank you for the compliment and the suggestion; this has been done in the revision.

+ There are two A-matrices in LCA: One is the Suh and Heijungs matrix of flows and the other one is the matrix of technical coefficients. Please distinguish better between the two, e.g., on P12L45, where you write about flows in the A\_f matrix, but it should read ‘coefficients in the A\_f matrix’.

In the revision, only the Leontief matrix is used. Other passages have been updated or removed.

+ P13L31: Only aggregated results can be reproduced from the aggregated foreground. Please make this limitation explicit.

Noted: "The aggregated result can also be computed from the aggregated foreground..." (p. 11, Eq.s 7)

+ P31L41: “Generally, any directed graph can be represented in Af ,…” That is not correct. Af can only contain bipartite graphs with a 1:1 correspondence between industries and nodes, that means, an industrial inventory (SUT) after allocation. Cf. DOI 10.1111/jiec.12306 for the argument.

Noted: "Generally, the foreground matrix A\_f can represent any process-flow model with a 1:1 correspondence between processes and flows, i.e. any allocated supply-and-use table..." (p. 13 bottom)

+ Figures 4 and 5: Units are missing. Is the rightmost column the row sum of the detailed exchange table? Please provide more explanations in the Table caption. The symbols A\_f, B\_f, etc. that are frequently used in the text should be displayed here as well.

These exhibits have been moved into the supplementary materials, but they have been updated both to include units on all rows and to make reference to the symbols introduced in Figure 2.

# Reviewer #3

The objective of the article is clear and the case for it well made. Despites minor mistakes the article is also well written. However, the article focuses on a very specific aspect of LCA and the results might be more suitable for the Int. J LCA.

Thank you for your positive review. I have considered submission to JLCA but I feel the JIE readership and editorial staff is more aligned with the paper's objectives of advancing disclosure and transparency at the present time. Additionally I was not happy with the formatting of the mathematics obtained in Kuczenski (2015), "Partial ordering of life cycle inventory databases", which I published in JLCA.

That said I found the paper interesting and I have some general comments which focus mostly on the discussion. ....

The added value of the proposed structured publication of results from a machine reading perspective is obvious. However its value added for the review process, comparison across models, benchmarking, etc. in the context of private data must be addressed from the outset. Otherwise the relevance and practicality of the proposed structure seems unclear.

Your commentary on the discussion was highly influential regarding the path I took with the revision. I strongly agree with your argument that overriding concerns about confidentiality and critical review both affect the usefulness of the proposed framework. Therefore in the revision I focused less on "publication" of the results and introduced both privacy protection and critical review as fundamental concerns.

The mathematical formulation is straightforward and shows a minimal set of data which should be included in a “research object”.

Please note that in the revision I have used the term 'disclosure' to refer to the "research object" of the initial manuscript.

1) Page 17 line 12: To my knowledge, this short sentence question the potential usefulness of the approach developed in the article. Data confidentiality in the proposed research object should be discussed more thoroughly, in particular with respect to the current critical review process in ISO LCA.

The referenced sentence was, "This is allowable if it is consistent with the author’s goal, and it will accordingly limit the ability of a data user to reproduce the model."

In the revision, the perspective taken is best summarized on p. 21 first paragraph, "…the reviewer must be granted access to both the public and private partitions in order to confirm that the partitioning is valid according to Eq. 9, and that b\_priv was computed correctly. However, the private information used in the computation can still be withheld from the disclosure." Here the reviewer, rather than the data user, is the primary audience, which is more consistent with current practice.

2) Page 17 line 40: Similarly, data confidentiality might result in a very sparse entity map. Can such a research object be organized in order to safeguard confidentiality and allow reproducibility of the results?

In the revision, this question is somewhat out of scope. Again, I agree with you and the focus is more on what the author chooses to disclose, for better or worse. The "disclosure completeness" metric (Eq. 13) also provides a measure of how much of the model's impacts are disclosed, which at least provides some intelligence to the general reader about the degree of transparency. If this metric is close to (or equal to) 0, then no significant information is disclosed. This may not be desirable, but at least it is clear.

3) Page 24 line 26: This is where it gets interesting, especially when the readers move to the supplementary information and pages 44 and 45, sections 2.4 and 2.5. Here the proposed research object is compared to current practice and the aggregation of foreground results for the sake of confidentiality.

Thank you for these comments. The referenced statement was, “Use of the research object to selectively exclude private data is discussed in the supplementary materials.” The material you referenced on "pages 44 and 45," which was of course in the supplementary materials in the first version, has now been moved to the main paper and made a centerpiece of the article. Additionally, "section 2.4", which dealt with partial background aggregation, has been expanded into a new main body section entitled "Reviewable Private Aggregation." I look forward with great interest to hear your thoughts on the revised version.