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LETTER TO THE EDITOR

Both completing system boundaries and realistic modeling of the economy are of interest for life cycle assessment—a reply to "Moving from completing system boundaries to more realistic modeling of the economy in life cycle assessment" by Yang and Heijungs (2018)

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Abstract
As Yang and Heijungs (Int J Life Cycle Assess https://doi.org/10.1007/s11367-018-1532-y, 2018) bring forward, there is indeed a need for "more realistic modeling of the economy" in LCA. However, what I discuss in this letter is that this does not imply that research should be "moving from completing system boundaries to more realistic modeling" or that "hybrid LCA with further linear sophistication is a step forward in the wrong direction", as Yang and Heijungs (2018) state. Five arguments are brought forward as to why not: (1) completing system boundaries is a fundamental aspect of LCA; (2) the approach that leads to a higher accuracy in LCA will in practice remain relative and case dependent; (3) the general argument of hybrid LCA is not that every economic activity is in theory connected; (4) hybrid LCA is applied for more reasons than just completing system boundaries; and (5) hybrid LCA is more a step forward in a pragmatic data-driven direction, which is not a wrong direction. Finally, I propose that a more broad empirical study is needed to pinpoint which type of adaptation might most probably lead to higher accuracy, keeping in mind that this still will never be completely generalizable.

Keywords Completing system boundaries · Realistic modeling · Life cycle assessment · Hybrid LCA · Linear modeling

Dear editor,

Yang and Heijungs (2018) present some interesting reflections and I agree that we should have a "more realistic modeling of the economy in life cycle assessment," with a focus on non-linear modeling and better consideration of market mechanisms. However, this does not mean that we should be "moving from completing system boundaries to more realistic modeling" or that "hybrid LCA with further linear sophistication is a step forward in the wrong direction," as the respective authors state. In this letter, I want to again argue that both types of research, "completing system boundaries" (incl. hybrid LCA) and "more realistic modeling of the economy," are relevant in the overall field of LCA, and which one should be a priori applied is always case dependent, i.e., not completely generalizable. Please see below five argumentations, which are to a considerable extent a repetition of arguments yet brought forward in previous works (Gibon and Schaubroeck 2017; Pomponi and Lenzen 2018; Schaubroeck and Gibon 2017).

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1 Completing system boundaries is a fundamental aspect of LCA

At the core of the concept of LCA is the consideration of a product's life cycle, i.e., expanding the system boundaries beyond the main production process and considering the interlinked processes. To state that we should in general "move from completing system boundaries," as Yang and Heijungs (2018) do, seems to be in contradiction with this core aspect of LCA. It has been shown that different rankings of alternatives, in terms of environmental impact, can be obtained when considering more steps in the life cycle, i.e., more layers (Lenzen and Treloar 2002). The response to Yang and Heijungs' (2018)

question "is a process-based LCA model with a complete global system boundary covering every single economic activity in every country a goal worth pursuing?" should not be no, from an absolute viewpoint, otherwise we should stop doing LCA altogether. However, if incorrect data or modeling is considered when expanding the system boundaries, this might lead to lower accuracy but this does therefore not mean we should move away from completing system boundaries in general.

2 The approach that leads to a higher accuracy in LCA will in practice remain relative and case dependent

Following on previous paragraph, which technique (e.g., hybrid LCA or considering non-linear modeling) will lead to a higher accuracy will be case dependent, more specifically dependent on the actual system but also on the available data and resources to perform the study. The case studies of Pomponi and Lenzen (2018) and Yang and Heijungs (2018) mainly point out that whether process-based or hybrid LCA will be more accurate is case dependent. However, what distinguishes the research supporting the statement of Pomponi and Lenzen (2018) that "hybrid LCA will likely yield more accurate results than process-based LCA" is that their research is of a more general nature. Yang and Heijungs (2018) study only a few examples which makes generalization of their conclusions quite incredible. Instead, Pomponi and Lenzen study various real economic systems and characterize them as having a higher interconnectivity, represented by a higher eigenvalue, for which hybrid LCA will, given the current available data, more likely show accurate results. However, as Pomponi and Lenzen (2018) also discuss, it is only an empirical average. Their analysis is also limited by characterizing real economies mainly by having flow matrices with higher eigenvectors. Besides the fact that their study provides more credibility (not certainty) to apply hybrid LCA instead of process-based LCA when studying real systems in current practice to obtain a higher accuracy, it still remains case dependent. Lastly, as Schaubroeck and Gibon (2017) state "the accurate result is commonly unknown. One can in practice often only presume that a more complete system boundary leads to more accuracy, as is the case for other choices. The practitioner should though reason its choice for hybrid LCA, as should likewise be done for any (major) choice in LCA conductance."

3 The general argument of hybrid LCA is not that every economic activity is in theory connected

Yang and Heijungs (2018) state that "The argument of hybrid LCA is that because every economic activity is in theory connected with every other one, […]" (without providing a citation) and "Gibon and Schaubroeck (2017) also seem to think LCA unveils "unintuitive relationships between products," which would justify the global all-inclusive system boundary (e.g., yoghurt in Netherlands connected to record companies in Andhra Pradesh India that produce Carnatic music)." Gibon and Schaubroeck (2017) have not stated that this justifies the global all-inclusive system boundary. In their work is just stated "To unveil unintuitive relationships between products is a strength of LCA" (Gibon and Schaubroeck 2017). They never stated that this justifies a global all-inclusive system boundary. These authors just said that there could be unintuitive relationships unveiled. Furthermore, Gibon and Schaubroeck (2017) stated that "the fact that the demand for a product automatically affects production in every single process of the worldwide economy in hybrid LCA is not true as it depends on the data and not only on the methodology." Even if some scientists would have stated that every economic activity is in theory connected, "it is important to distinguish the intention of the application from the application itself (one could even distinguish between data and method), when judging" (Schaubroeck and Gibon 2017). Gibon and Schaubroeck (2017) even show with numbers that not all processes are interlinked in an IO database. Related to this matter, Yang and Heijungs (2018) state: "Consider, again, the US corn ethanol example: its impacts on Chinese stuffed animal production traced through the supply chain are implausible and unlikely." This is a presumptuous statement. It would seem more scientific to actually proof it is not the case instead of speculating based on preconceptions. Their statement is a marginalization of the drive to complete system boundaries by bringing forward some untested connection that seems implausible. The same goes for other similar statements of Yang and Heijungs (2018): "What is, for example, the likelihood that a once-only tiny-scale indulgence in yoghurt in Netherlands would lead souvenirs stores in Yunan China that make and sell indigenous customs to tourists or record companies in Andhra Pradesh India that produce Carnatic music to expand? None." Gibon and Schaubroeck (2017) yet brought forward that even in process-based LCA peculiar connections are made: "For example, a quick calculation of a process-based LCA using ecoinvent 3 .1 (consequential) shows that as much as 9.5 g of palm fruit bunches ("Palm fruit bunches, at farm/MY") is necessary to produce one additional kilogram of an integrated circuit board ("Integrated circuit, IC, logic type, at plant/GLO"), via the production of soap from palm oil for wire drawing." A more correct argument for hybrid LCA seems to be that every economic activity could be indirectly connected. On a side note, Yang and Heijungs (2018) use a fishing net as a metaphor for a linear model of the economy. When lifting a certain knot, for more adjacent knots, representing closer linked processes, the extent of the lift will be much bigger than for less adjacent knots. Although this representation is quite limited, it would seem better to regard the fishing net in three-dimensional space.

This would show that a lot more knots will raise in the nth layer, making possibly the increased total lift, and thus effect, much more considerable for that nth layer.

Lastly, it is also not fixed at which upstream or downstream layer the hybridization will be made. IO sectors or processes may not only be added or replaced at the furthest layer in hybrid LCA. Hybrid LCA is not an approach that may only be used to extend the system boundary but it can also be used to improve data quality. See the next section.

4 Hybrid LCA is applied for more reasons than just completing the system boundary

The main drivers for hybrid LCA in the work of Yang and Heijungs (2018) appear to be that of completing system boundaries. What seems completely overlooked in their work is the other reasons to apply hybrid LCA besides completing system boundaries. As Schaubroeck and Gibon (2017) wrote "in practice, the potential benefit of combining input–output-based and process-based life cycle inventories goes beyond a possible improvement in accuracy through expanding the system boundaries (Gibon and Schaubroeck 2017). For the sake of clarity, Table 1 lists some characteristics of both approaches that can be combined to provide an improved life cycle inventory. These other potential benefits are yet again not only methodology-dependent but also data-dependent." Please see the respective table in the manuscript for an overview. Schaubroeck and Gibon (2017) also exemplified this: "For example, Gibon et al. (2015) have applied hybrid LCA among else because they (1) presumed more accuracy through an expanded system boundary (to include business services via EXIOBASE) but also (2) to create a presumed better geospatially differentiated (using a multiregional but less detailed IO-database EXIOBASE) but also detailed (using the detailed but less spatially differentiated process-based ecoinvent 2.2 database) electricity production life cycle inventory." These other reasons for application negate the reduction of comparing hybrid LCA with process-based LCA solely based on the accurate completeness of system boundaries, i.e., including more processes or sectors, as done by Yang and Heijungs (2018).

5 Hybrid LCA is more a step forward in a pragmatic data-driven direction, which is not a wrong direction

I agree with Yang and Heijungs (2018) that, from a theoretical viewpoint, process-based LCA has "unrealistic assumptions such as linearity and omission of price effects and various constraints" and that "Hybrid LCA, through adding the IO model, doubles down on the linearity and narrowness of process-based LCA." However, I disagree with the consecutive conclusion that it is "thus is a step forward in the wrong direction" as they state. It is quite clear that the concept and mathematical backbone, i.e., the linear framework, are quite similar between hybrid LCA, process-based and IO-based LCA, and that these have their limitations. Yet, hybrid LCA paves the way for a manifold of combinations of IO data and process-based data, this more precisely combining respective databases, e.g., EXIOBASE and ecoinvent. Indeed it is, in some cases, not a giant leap forward in methodological development but rather an improvement in considering more and different data. After all, the quality and pragmatism of the usage of a model is dependent on the quality of and readily availability of input data to run it. An improved theory or methodology alone will not suffice to obtain adequate results. As Gibon and Schaubroeck (2017) mentioned "While technically unrealistic, linearity is a necessary evil that LCA practitioners often have to accept because of data collection and computation time limitations to face when addressing non-linearity" and "In fact, one should, at best, only judge whether a practical LCA approach is novel or advanced enough in light of the current state of the art, and this keeping in mind practical limitations." Pomponi and Lenzen (2018) point similarly out that "we should try to challenge the *status quo* bearing in mind that LCA will be used as a tool for real-life application and not in a mathematical exercise." If we would always limit applications of LCA approaches because of theoretical issues, we would never be able to apply them and provide any requested feedback to current policy makers, due to the inevitable incompleteness and error of mathematical models. The aspect of higher data availability and potentially quality when considering a combination of process-based and IO-based data (and also pragmatism in general) as drivers for hybrid LCA appears to be overlooked in the work of Yang and Heijungs (2018).

6 A path forward for this scientific dialog

To conclude, I agree with a manifold of the statements of Yang and Heijungs (2018) but they should avoid general or absolute statements against the principle of completing system boundaries or hybrid LCA. There are no "wrong directions" in an absolute way, only probably less interesting directions from a relative perspective. In this sense, it is striking that some statements of Yang and Heijungs (2018) on the same matter are relative and case dependent (e.g., "a process model with a complete global system boundary is not a goal worth pursuing for *most* policy-relevant studies") and others are absolute (e.g., "Adding IO to the process model with further linear sophistication doubles down on the unrealism of these assumptions and thus *is a step forward in the wrong direction*"). Which perspective do they take?

To be able to tell what the focus of improvement should be is only possible when the actual error on the outcome can be

estimated, which is practically infeasible in LCA. There are a manifold of aspects in which LCA should be improved, including (a) consideration of market mechanisms, (b) going towards non-linearity, and (c) completing system boundaries. In scientific research, we need to focus on all of these to some extent.

It would be advised to show on a quantitative, systematic, and relative basis that outcomes could have changed more, starting from process-based LCA, by considering a certain type of realistic modeling instead of doing hybrid LCA, in a representative sample of realistic cases or based on their empirically average characteristics. If this could be done, it would not make it an absolute requirement to prioritize such realistic modeling of the economy, but would make it more credible and likely relevant to do so for such type of realistic cases in practice. This is also, in my opinion, how Pomponi and Lenzen (2018) have approached it: by considering a manifold of realistic systems and their respective characterization of having on average higher eigenvalues. Finally, I rather think there will be a shift in pragmatic research of more realistic modeling of the economy if such a type of method is developed that can be systematically applied and for which data is adequately readily available.

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