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COMMENTARY AND DISCUSSION ARTICLE

Does hybrid LCA with a complete system boundary yield adequate results for product promotion?

Yi Yang[1]

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Abstract
Purpose Hybrid life cycle assessment (LCA) with a complete system boundary is recognized as an advanced approach widely applied in comparative analysis with the goal of product promotion. Here, I evaluate the theoretical foundation, or assumptions, of hybrid LCA in this application and discuss alternative models. The goal of this article is partly to call attention to the restrictive assumptions involved in the models used in LCA and to instigate further research and effort to improve these models.
Methods As with process-based LCA, hybrid LCA is a type of linear model when it is used to estimate changes. It relies on several restrictive assumptions such as fixed input/output coefficients and unlimited supply of inputs. Besides, hybrid LCA further rests on the assumption of economy-wide effect, i.e., a change of any magnitude in the output of any product would affect the entire economy. This may be another restrictive assumption, and to what extent it is reasonable depends on an array of factors, including the product being studied, its role in the economy, the magnitude of change, and the structure of the economy.
Results and discussion Because of the restrictive assumptions, hybrid LCA may not necessarily yield adequate results for product promotion. This, however, does not mean that it entirely falls short, but that the assumptions need to be scrutinized and determined if they reasonably reflect the reality. If so, the results yielded by hybrid LCA may be adequate. But if not, the results fall short, and further research is needed.
Conclusions For comparative analysis with the goal of product promotion, understanding how increases in the output of the product being studied would affect the economy is crucial. And this should form the basis of decision making. Alternative models to consider for large-scale changes include computable general equilibrium models and rectangular choice of technology models, recognizing their limitations and assumptions as well. Alternatively, one may use simpler models such as process-based inventory but build scenarios to study how the impact of product promotion may ripple through the economy.

Keywords Hybrid LCA · Life cycle assessment · Process-based LCA · Product promotion

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✉ Yi Yang
yyandgin@gmail.com

[1] CSRA Inc, 3170 Fairview Park Drive, Falls Church, VA 22042, USA

1 Introduction

One of the principles of life cycle assessment (LCA) that have gained a wide consensus is the selection of a complete system boundary (Suh et al. 2004). This has given rise to the development of hybrid analysis, which incorporates input-output (IO) models into process-based LCA (Heijungs and Suh 2002). Process-based LCA is argued to suffer from truncation errors (Lenzen 2001). Because a complete database is yet to be developed that covers every single process of an economy, process-based inventory compilation is bound to cut off somewhere along the supply chain, hence the truncation errors. IO models, on the other hand, cover an entire economy, although in aggregated forms. Through combining process and IO models, hybrid LCA is argued to possess specificity and system completeness and is broadly recognized as an advanced approach in LCA (Wiedmann and Minx 2008).

It has also been argued that hybrid LCA, with a complete system boundary, yields more robust results for product promotion, than process-based LCA with an incomplete system boundary (Suh et al. 2004). Over the past decade, hybrid LCA has been increasingly applied in comparative analysis and to a wide range of products (Nakamura and Nansai 2016). Here, I evaluate the theoretical foundation, or assumptions, of hybrid LCA when it is used with the explicit purpose of product promotion. The central question I seek to address is, whether hybrid LCA, with a complete system boundary, provides adequate results for product promotion. This has not been done thus far. Nakamura and Nansai (2016) recently provided an extensive review of hybrid LCA, but they focused more on model set-up than on the assumptions behind.

I first use an example to illustrate the common use of hybrid LCA and then dissect the assumptions involved in the conclusions reached in the example. In so doing, I show that because of relying on highly restrictive assumptions, hybrid LCA does not necessarily yield adequate results for product promotion. This may be true of hybrid LCA based on inventory data reflecting the status quo or inventory data simulated for the future. Finally, I discuss alternative approaches to product promotion. The goal of this article is partly to call attention to the restrictive assumptions involved in the models used in LCA and to instigate further research and effort to improve them.

I should point out at the outset that I shall avoid getting into the debate and dichotomy between attributional LCA and consequential LCA (Finnveden et al. 2009). Partly, the divide seems to cause confusion rather than add clarity, given my experience as a reviewer, discussions I had with colleagues, and feedback I received from presentations. It is unclear, for example, if the recent debate (Suh and Yang 2014; Anex and Lifset 2014) has left the LCA community any clearer about the issue. More importantly, on a fundamental level, the two frameworks may not be so different from each other. Consequential LCA studies how a system responds to decisions, and causality is at the core of the framework. But causality may also be a critical element of attributional LCA. This is not a novel view. For example, Wiedmann and Minx (2008) define carbon footprint, a classic product of attributional LCA, as "a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly *caused by* an activity or is accumulated over the life stages of a product." Finally, I believe the concepts of LCA can be articulated in simpler terms by clearly defining research questions and specifying models to be used (e.g., linear, non-linear) and associated assumptions.

2 An example of hybrid LCA

Suppose two alternative products, X and Y, produced by very different technologies, are compared with the aim of promoting the one estimated to have a lower carbon footprint. The results, using process-based LCA (Eq. 1) with inventory data reflecting the status quo, show that X has a slight advantage, with a carbon footprint of 4.5 kg/unit, 10% lower than that of Y (5 kg/unit).

$$m = BA^{-1} f \tag{1}$$

where **B** is the environmental matrix, **A** the technology matrix, and **f** represents functional unit (Heijungs and Suh 2002). But because the process inventory is incomplete, so the argument goes, both product systems suffer from truncation errors with unknown magnitude. And given the closeness of the results and possibly other uncertainties (e.g., due to allocation), we would be hesitant to conclude that X is a clear winner, thus not so confident to suggest promoting it. However, further analysis using, for example, the tiered hybrid LCA (Eq. 2) reveals that X's carbon footprint is 5 kg/unit but that of Y is about 7 kg/unit. In other words, the original process inventory underestimated X's footprint by 0.5 kg/unit and Y's by 2 kg/unit.

$$m = \begin{bmatrix} B & B^* \end{bmatrix} \begin{bmatrix} A & 0 \\ U & I - A^* \end{bmatrix}^{-1} f \tag{2}$$

where $\mathbf{B}^*$ and $\mathbf{A}^*$ are the environmental and technology matrices of IO-based LCA and **U** is the upstream matrix that contains the missing parts in the process model, **A** (Suh and Huppes 2005). **U** serves as a connector, through which the missing parts of the process model are estimated by the IO model. Considering that now each product achieves an equivalently complete system boundary and that X's advantage grows to nearly 30%, which probably outweighs other uncertainties, we believe the revised results based on hybrid LCA are more robust. Therefore, we would be more confident to suggest promoting X.

3 Assumptions of hybrid LCA

There is a sequence of arguments in the above example that warrant close examination. First, what are the reasons for questioning results from a process inventory with an incomplete system boundary, or what are the justifications for a more complete system boundary? As the process-based inventory reflects the status quo, it is possible that the production of X or Y has caused certain activities along the supply chain that are not covered by the inventory. In this case, estimates derived from the process inventory may underestimate the true life-cycle emissions caused by the two products.

By adding an IO model to complete the system boundary, however, it assumes that X or Y has caused or contributed to part of the production of every single process or industry in the economy being studied (which, with globalization, basically means the world economy), regardless of what X or Y is and other factors. This may be a strong assumption that needs further theoretical reasoning and empirical verification. To what extent the making of a product has affected the rest of the economy depends on, for example, the role the product plays in the economy and the structure of the economy per se. If it is a major product with significant economy-wide pulling effects (e.g., it produces a large economic output and relies on intensive use of a wide range of intermediate inputs), this assumption may be applicable. However, if it is a marginal product with limited pulling effects, this assumption may not be so applicable. To take an extreme example, it would be hard to justify that a tiny device made specially for the large hadron collider (LHC) in Geneva would have affected olive oil production in Italy, or bamboo shoots cultivation in China, or durian growth in Thailand. But this is essentially the argument of hybrid LCA with a complete system boundary.

Second, what does it exactly mean by that because product X has a lower carbon footprint than its alternative Y in the status quo, X can be promoted? This must mean that an *additional* unit of X would generate the same life-cycle carbon emissions as an existing unit, thus it would maintain the same advantage over Y. In other words,

$$\begin{bmatrix} B & B^* \end{bmatrix} \begin{bmatrix} A & 0 \\ U & I-A^* \end{bmatrix}^{-1} \mathbf{f_0} = \begin{bmatrix} B & B^* \end{bmatrix} \begin{bmatrix} A & 0 \\ U & I-A^* \end{bmatrix}^{-1} \mathbf{\Delta f} \quad (3)$$

where $\mathbf{f}_0$ indicates a unit of X in the status quo modeled by the environmental and technology matrices, and $\Delta\ \mathbf{f}$ indicates an additional unit. This also means that the additional unit of X would affect every single process or industry included in the technology matrix, causing them to expand a little bit to accommodate the additional production. Again, to what extent the additional production of X has such broad-scale, economy-wide impacts depends partly on the role X plays in the economy and the structure of the economy, and partly on the magnitude of the additional production itself. And again, to continue with our extreme example, it would be hard to justify that a replacement for the tiny device used in the LHC would cause a bit more production of olive oil in Italy, or bamboo shoots in China, or durian in Thailand.

For major products with significant economy-wide pulling effects, this assumption of a complete system boundary may be justifiable, although the magnitude of additional production should be factored in. But even for these products, the likelihood that their life-cycle emissions of an additional unit would be the same as that of an existing unit is probably low given that there are several other restrictive assumptions involved (Yang 2016). The fact that the technology and environmental matrixes in Eq. 3 remain unchanged is equivalent to linear extrapolation, with several underlying assumptions. It assumes, for example, fixed input/output relationships and unlimited supply of inputs or capitals for all processes or industries covered. It also assumes that any coproducts produced by the economy are adequately absorbed by the market without unintended side effects.

The reason these are likely restrictive assumptions is that many industries may be faced with constraints (e.g., arable land and rare earth) (Sandén and Karlström 2007; Fargione et al. 2008), many may benefit from economies of scale (Krugman 1980) or experience diseconomies of scale, and yet some coproducts generated may disturb the structure of the economy. Depending on how these factors play out, linear extrapolation from the status quo may lead to under- or over-estimation or rough approximation of the true life-cycle emissions of additional production (Fig. 1).

One may argue while hybrid LCA based on the status quo may fall short of product promotion, what about hybrid LCA using inventories simulated of the future? In dynamic life-cycle inventory analysis, it is common to generate multiple inventories reflecting an evolving system that typically becomes more energy efficient and less material-intensive (Hertwich et al. 2015). To use the example above, suppose we construct a future hybrid inventory in which the process producing X has expanded and become even more efficient, and in which other processes have in general also become more efficient. This inventory would yield a carbon footprint of 4 kg/unit for X, and 6.5 kg/unit for Y, with the advantage of X becoming even larger (about 40%). Should we now conclude that X is worth promoting?

The answer is again, not necessarily, and caution should be exercised. Future inventories are often constructed by simply modifying technological and environmental coefficients for some of the key processes, such as the reference process being studied in the foreground system and energy sectors in the background system. There are no attempts to estimate the potential impacts of the expanding reference process on other processes. Damages could have occurred in the process of expansion, but may not at all be captured by the future inventories. An example of the sort is U.S. corn ethanol. Because of improving yield at both farmland and biorefinery, the life cycle emissions of corn ethanol were estimated to have decreased from early 2000s to late 2000s (Liska et al. 2009). However, the expansion of the ethanol sector may have caused detrimental land use change (LUC) effects (Fargione et al. 2008; Searchinger et al. 2008) through market-mediated mechanisms that were not at all captured by the inventories cited. Therefore, a future inventory that relies on simple modification of coefficients without capturing important market changes may too not yield adequate estimates for product promotion (see more discussion in the Electronic Supplementary Material).

In summary, because of the restrictive assumptions discussed above, hybrid LCA, with a complete system boundary, may not necessarily yield adequate results for product promotion. The point, however, is not that it entirely falls short, but that we need to scrutinize the assumptions and

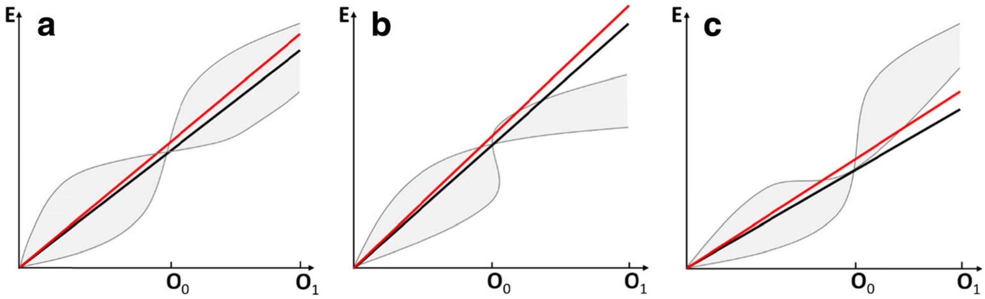

Fig. 1 An illustration of the use of hybrid LCA for product promotion with three outcomes: **a** adequate approximation, **b** overestimation, and **c** underestimation. *O* represents output of the product being studied, and *E* life-cycle emissions. O_0 symbolizes current output and O_1 projected output after product promotion. *Gray lines* and *areas* indicate the true life-cycle emissions as a function of output. The reason to present the true values in range, as opposed to point estimates, is to show the uncertainty involved in puzzling out what has happened in the past, and to demonstrate the range of possibilities of what could happen in the future. *Black lines* represent process-based LCA while *red lines* represent hybrid LCA, which yields larger results for covering a more complete system boundary. Depending on how the system responds to the additional production (O_0-O_1), hybrid LCA could lead to adequate approximates, over-, or underestimates

determine if they adequately or reasonably reflect the reality. If so, the results may be adequate. But if not, the results may not be adequate, and further research is needed, e.g., by considering constraints and how industries facing them would respond during expansion (Yang 2016).

4 Alternative approaches

For comparative analysis with the goal of product promotion, instead of defaulting to hybrid LCA and a complete system boundary and assuming a linear relationship for additional production, it is important to study the potential and actual impacts of product promotion. This approach entails us to examine closely how our economic system operates internally and how it may respond to external perturbations such as the promotion of a product. Information on, for example, what constraints different processes or industries face and how their technological and environmental structures may change in response to change in output, need to be collected beyond our conventional inventory compilation. If (1) an economy is largely unconstrained with abundant natural resources, labor, and capital, (2) its structure is relatively fixed, and (3) the product being studied has significant economy-wide pulling effects, this approach would yield similar results as given by hybrid LCA. In this case, hybrid LCA is a special case of the more generalized approach.

Systemic models employing such an approach include general equilibrium (CGE) models (Tyner and Taheripour 2008), which are non-linear optimization based, and rectangular choice of technology (RCOT) models (Duchin and Levine 2011), which are linear optimization based. These models account for broader aspects of the economy, such as constraints, than our conventional inventories. But it should also be pointed out that these are sector-level models suited more for large-scale changes, and they rely on other restrictive assumptions that need to be recognized, such as systemic optimization (Rose 1995). Alternatively, one may rely on simpler models such as process-based inventory but build scenarios to study how the impact of a decision may ripple through an economy (Yang 2016). In the scenarios, different techniques, such as statistics modeling or optimization, may be used to the extent justifiable, and factors such as constraints and economies of scale can be considered.

As opposed to sophisticated models such as CGE and RCOT, which are constrained by the relationships in the input-output accounts reflecting largely the status quo, another benefit of scenario modeling using simpler models is that creative and futuristic scenarios can be constructed to capture improvement opportunities that do not yet exist. For example, local food is often discouraged as transportation is found to be a minor source of emissions (Weber and Matthews 2008). But this conclusion assumes that transportation is the only benefit of food localization, ignoring other potential benefits local food can uniquely enable, including the recycling of energy, nutrients, and water (Yang and Campbell 2016). These opportunities do not yet occur, but they can be creatively investigated to provide a more comprehensive landscape of the benefits of food localization such that consumer decisions and policy making can be better informed.

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