Editorial

Title: Advancements in Integrated Assessment Approaches in Industrial Ecology

Special Issue on Charting the Future of Life Cycle Sustainability Assessment

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<Introduction>

Products and services are the key selling items of our economic system, while they are also key concepts in addressing contemporary sustainability challenges. Refrain from any consumption is not an option, so we must strive for a more sustainable production and consumption pattern, while knowledge of the sustainability of products is a requirement. One of the assessment methods widely used for this over the past 30 years is *environmental* Life Cycle Assessment (LCA), commonly truncated to simply Life Cycle Assessment or LCA. Nearly a decade ago, the concept of life cycle sustainability analysis (LCSA) emerged out of LCA. The more comprehensive LCSA has been widely discussed and debated ever since. LCSA embodies many aspects that attract researchers and practitioners alike, to the field of Industrial Ecology. The field of LCSA is transdisciplinary, quantitative in approach, and for new areas, particularly aspects of Social LCA (S-LCA), open to methodological development. Based on those experiences, this is an appropriate time to assess the progress of LCSA and grapple with its continued development. What exactly does the community of LCA researchers and users consider LCSA to be, and what are the major challenges to LCSA?

Some view LCSA as a broadening of environmental LCA (E-LCA) to also include economic (through life cycle costing; LCC) and social impacts (through social LCA; S-LCA) (Klöpffer and Renner 2007). Others view it as a trans-disciplinary framework for the integration of models rather than a model (Guinée et al. 2011). In this latter view, LCSA then not only looks at enlarging the scope of indicators, but also at the expansion of the object of analysis from products to sectors to whole economies, and at deepening of modeling to both better characterize and include more mechanisms. According to Guinée et al. (2011), LCSA incorporates a plethora of disciplinary models and guides selection of the most appropriate to address specific sustainability questions. Structuring, selecting, and making those disciplinary models available for application to diverse types of life cycle sustainability questions is a central challenge. Within this broader view, traditional E-LCA still has its value fulfilling one specific requirement of this broader life cycle sustainability framework.

The expansion of E-LCA towards LCSA is a consistent and natural progression to the achievement of the overarching goal of assessing the relative sustainability of a system. In this light, three questions need to be addressed: First, what form should the integrated concept take to include technological, economic, and social assessment of systems? Second, what are the precise classifications of application? Over the past decade, LCA has been successfully applied at the product level. Can LCSA be applied at the organizational level or the economy-wide level? If so, what are the rules for boundary definition? And, how do these various levels of applications relate? Third, international consensus has been achieved regarding the most important sustainability aspects to address through the United Nations' Sustainable Development Goals (UN SDGs). Is it possible for LSCA to adapt and adopt methods to quantify and measure progress toward sustainability? Further, will this expansion of E-LCA to LCSA enhance our ability to apply life cycle thinking in the use of other industrial ecological tools and concepts, including industrial symbiosis and material flow analyses?

This special issue seeks answers to these questions as part of our concerted effort as a community of LCA researchers and users to reinforce the pertinence of the life cycle concept and industrial ecology to the latest thinking in sustainable development. The articles in this special issue advance the discussion of these questions along four lines:

1) conceptual challenges of '*broadening of impacts*' while maintaining a cohesive, yet comprehensive approach (Schaubroeck & Rugani 2017);

2) communicating LCSA results to decision-makers applying weighting schemes and dealing with value choices and subjectivity (Wulf et al. 2017; Kalbar et al. 2017; Grubert 2017);

3) how to deal with technological, economic and political mechanisms at various levels of analysis through linking or integration of LCA with other types of models (Wu et al. 2017; Plevin 2017; Kua 2017);

4) developing proper, preferably quantitative and practical, approaches for S-LCA (Kühnen & Hahn 2017; Hardadi & Pizzol 2017; Corona et al. 2017; Suckling & Lee 2017). We discuss each of the lines and the contributions to further development published in this special issue.

<heading level 1> Broadening of impacts (Schaubroeck & Rugani 2017)

The LCSA definitions proposed by Klöpffer and Renner (2007) and Guinée et al. (2011) both adopt the environmental Areas of Protection (AoPs) as originally defined by Udo de Haes et al.

(2002). Since this time, no separate AoPs have been defined for the economic and social pillars. In this special issue, Schaubroeck & Rugani (2017), and Huang (2017) discuss some challenges related to the broadening of impacts and propose ways forward.

In the Forum article by Schaubroeck and Rugani (2017), the authors raise three conceptual challenges to advance this field: (1) framing which areas should primarily be sustained and hence on which the impact should be assessed (2) accounting for the interconnectedness among AoPs, and (3) the assessment of both benefit and damage to the AoPs, the emergent net positive domain. At the center of this work is the reflection and awareness that sustainability is inherently anthropocentric. In this regard, other entities such as ecosystems are sustained for the benefit of human well-being. Well-being adjusted life years (WELBY) is suggested as most promising holistic indicator for the next level of LCSA.

<heading level 1>Communicating LCSA results (Wulf et al. 2017; Kalbar et al. 2017; Grubert 2017)

When broadening the scope of environmental life cycle indicators to also include economic and social indicators, LCSA practitioners are challenged to think on how to communicate their results to decision-makers. This communication may imply weighing and aggregating indicator results by, for example, applying (multi-criteria) decision analysis methods (Guinée 2016). In this special issue, Wulf et al. (2017), Kalbar et al. (2017), and Grubert (2017) investigate preferred practices to obtain single scores.

Wulf et al. (2017) use the results of an E-LCA, a LCC assessment, and S-LCA to examine a complex product: a rare earth permanent magnet for use in wind turbines. The article presents different approaches for combining the results of separate assessments with its attendant methodological challenges. Different normalization, aggregation methods, and weighing factors are applied and their impacts on the results are compared. Results show that the normalization method applied has a greater influence on the overall results than the aggregation method or weighting factors. Additionally, this study shows that indifference thresholds should be applied to avoid overestimation of small impacts. Indifference thresholds ensure that impact categories with nearly the same results for all analyzed options are treated as identical results. The study stresses the importance of questioning desirable differences in compensation between impacts. Despite the impact of these factors, the case study of permanent magnets with different supply routes for rare earths, in this case, the three regions of: United States, Australia/Malaysia, and China, demonstrates the ranking of Chinese production as the most problematic, irrespective of the approaches applied. The Chinese supply route is shown to be comparable only when economic aspects are weighted more highly than environmental and social, raising thoughtful questions regarding the dominance of sourcing rare earth metals from China.

Kalbar et al. (2017) examine more closely aspects of weighting and aggregation. The authors argue that the widely used ReCiPe life cycle impact assessment (LCIA) single score method does not account for either the effect of dominating alternatives (i.e., alternatives having high values across all endpoints) or the interdependency of the indicators being aggregated (Huijbregts et al. 2016). ReCiPe uses the Linear Weighted Sum (LWS) method, and Kalbar et al. (2017) found that LWS was not capable of accounting for the effect of weighting schemes (hierarchical, individualistic and egalitarian perspectives) and thus not able to fully represent different stakeholders’ perspectives. As an alternative, they propose a distance-based Multiple Attribute Decision Making (MADM) method to obtain single scores. This method was found to be more suitable in the process of estimating single scores.

Grubert (2017) examines the challenges of incorporating subjective information necessary for defining the major elements of a decision based on an LCSA study: prospects to decide among, uncertainty, risk attitudes, and preferences in this decision framework. The author argues that given LCSA’s "broad scope, explicit and standardized inter-category preferences are important for improving its value for decision makers". From the author's perspective, LCA practitioners should not be solely responsible for the value judgments necessary to integrate impact categories within and across any of the three evaluations of LCSA (E-LCA, S-LCA, and LCC). They argue further that this task should not fall entirely to decision makers as well, as life cycle based decisions are highly sensitive to value frameworks. They posit that the audience of LCSA studies, such as, individuals and decision-makers alike, are unlikely able to "meaningfully interpret, evaluate, and determine tradeoffs without support". The author proposes that LCSA leverages its multiple paradigms to generate "explicit, empirically grounded inter-category preference archetypes for use in evaluating decision robustness". The author provides a proof of concept through the application of environmental, social and economic issue in the United States value-context.

<heading level 1> Linking or integration of LCA with other types of models (Wu et al. 2017; Plevin 2017; Kua 2017)

As part of deepening and covering more mechanisms than just technological (Guinée et al. 2011), LCSA may also aim to sophisticate existing models (refining spatial and temporal dimensions, for example) and/or combine and sometimes integrate LCA with different methods. In this special issue, Wu et al. (2017), Plevin (2017), and Kua (2017) investigate options for sophistication of existing life cycle and inclusion of other models.

Wu et al. (2017) state that the current aggregate and top-down LCSAs generally fail to account for spatial, temporal and emergent behavioral dynamics during the life cycle inventory (LCI) analysis phase of a study. The authors suggest an integration of an agent-based modeling approach with particularly the LCI phase. Using a hypothetical example of green building development, the agent-based modeling approach is compared with a pre-defined static policy model. The results confirm that there are temporal and spatial variations caused by behavioral dynamics by integration of agent-based model results into the LCI phase. The results are then integrated into the calculation of temporally dynamic LCSA indicators with an annual basis.

Plevin (2017) investigated using an integrated assessment model (IAM) as a platform for CLCA of biofuels. In this article focus is on the methodological challenges of this approach. Part 2, forthcoming, will present a case study using one IAM—the Global Change Assessment Model (GCAM)—to estimate the climate effects of several biofuels. The bottom-up integrated approach presented in Part 1 demonstrates the importance of IAMs, as they can identify important dynamics missing from simpler CLCA approaches, such as "market interactions, climate system feedbacks, changes in population and GDP and technical learnings". Plevin found that fuel policy actions may have unintended consequences that cascade through global markets, resulting in non-negligible GHG emissions elsewhere, potentially undermining policy goals.

In the Forum article, Kua (2017), the overall approach to defining a LCSA framework is challenged, as it is claimed that it does not adequately consider the role of stakeholders in the assessment process, rebound effects, and how the concept of vulnerability, resilience and stakeholders' risk aversion can be applied to life cycle thinking. A more comprehensive framework, Life Cycle Sustainability Unified Analysis (LiCSUA), is proposed to address these key four issues, while preserving and incorporating key features of the existing LCSA framework by Klöpffer and Renner (2007) and the LCSA framework under the CALCAS (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability) effort, commissioned by the European Commission (Heijungs et al. 2010). The LiCSUA approach crosslinks indicators, inter- and intra-dimensional consequences, rebound effects, and potential "transitioning" of these indicators into a single framework.

<heading level 1> Approaches for S-LCA (Kühnen & Hahn 2017; Hardadi & Pizzol 2017; Corona et al. 2017; Suckling & Lee 2017)

The challenge to develop appropriate, preferably quantitative, and practical indicators for S-LCA has been present ever since S-LCA was proposed. Most efforts so far have focused on finding and developing ways to include social impacts using impact categories and indicators, similar to environmental LCA. In this special issue, Kühnen & Hahn (2017), Hardadi & Pizzol (2017), Corona et al. (2017), and Suckling & Lee (2017) explore the challenges and options to further and practically apply S-LCA.

Kühnen and Hahn (2017) argue that S-LCA is still at a "developmental stage", and is "fragmented and lacks a foundation on empirical experience". The primary reason is the "absence of general standardized indicators that clearly reflect and measure businesses' social impact along product life cycles and supply chains". They provide a comprehensive assessment of the state of research on S-LCA indicators across industry sectors. Through their systematic review of "trends, coherences, inconsistencies, and gaps" in research on S-LCA indicators they find that researchers interests are broad, however, they lack sufficient empirical investigation to shift from the field from primarily a-theoretical to one based on theory and guiding principles. They found that often researchers concentrate heavily on worker- and health-related indicators and overlook important social core issues, fair competition, community engagement and prevention and mitigation of conflicts. Kühnen and Hahn (2017) synthetize the most important indicators used in research as a step toward standardization, highlight important trends and gaps, and emphasize critical deficiencies in the S-LCA field.

Hardadi and Pizzol (2017) apply a Multiregional Input-Output (MRIO) framework to LCSA by extending the framework to also include social dimensions. In this context, they propose that the ideal framework should be a MRIO database to investigate not only environmental footprints but also social footprints. They extend the traditional MRIO Framework by including five indicators (social 'inventory results') available from the International Labor Organization (ILO): employment, working hours, salary, occupational accident cases, and unemployment. The authors develop a characterization step whereby indicator values are converted into social impacts on human productivity and human well-being measured in Quality Adjusted Life Years (QALYs).

In Corona et al. (2017), the three-pillar framework, namely economy, environment and society of LCSA is also accepted, however, S-LCA is perceived as novel, and still under development. Corona et al. (2017) apply the same structure as E-LCA to S-LCA, to maintain continuity with the standard LCA approach, suggesting new classification and characterization models. For their social life cycle inventory, the authors apply the same indicators proposed by the UNEP/SETAC Guidelines on S-LCA, as defined by the Social Hotspots Database (SHDB) (Benoit-Norris et al. 2012). However, for the impact assessment phase, a new social performance method is suggested, which builds on Performance Reference Points, an activity variable and a numeric scale with positive and negative values over a range of -2 to +2. The social performance indicator applied shows that the deployment of a solar power plant in Spain increases social welfare, especially in the impact categories of socio-economic sustainability and fairness of relationships.

Suckling and Lee (2017) explore empirical end-of-life (EoL) options for mobile phone by integrating E-LCA and S-LCA. Mobile phones offer many potential social benefits throughout their lifetime, but this lifespan is often much shorter than design intent. Reuse of the phone in a developing country allows social benefits to be fully realized. Under the current state of development of recycling infrastructure, recovery rates of phones after reuse are very low in many markets. To recover materials effectively, the authors suggest recycling in developed countries may be the best option, but at a cost of the ability to reuse the phones. This effort would involve obtaining sufficient geographical and temporal detail of the end of life options to evaluate the more sustainable scenario. The author's urge caution as the numerous challenges may mount up to make performing life cycle assessment of mobile phones unwieldy. Instead of trying to encompass every aspect in full, focus should be given to answering a question which has the best chance of being answered.

<heading level 1> Concluding Thoughts

Reflecting on the manuscripts selected for publication in this special issue, we clearly see advancements in the further development of LCSA. However, we also conclude there are several challenges identified in Guinée (2016) still not being addressed or solved. From the manuscripts received, we have found that there are many fundamental conceptual challenges raised, such as which areas should be selected as primary to be sustained and how to handle the interconnectedness of those that are selected, and further how to incorporate both impacts and benefits within the same framework (Schaubroeck and Rugani 2017). The trend appears to be focus and prioritization of impacts versus broadening of impacts.

A highlight observed is progress on communication. Critical thinking regarding techniques of normalization, weighting and aggregation are at the forefront of applying LCSA, resulting in part, to move towards more traditional analytical tools such as MADM approaches, to both midpoint and endpoint methodologies. Awareness that the LCSA practitioner should not be the sole purveyor of what is most important, and preferences should be “empirically-grounded” archetypes (emphasis on the plural) to support evaluations that lead to robust decisions. Even still, more direct attempts to address challenges identified by Guinée (2016) include dynamic (Wu et al. 2017), integrated (Plevin 2017) and comprehensive approaches (Kua 2017). However, at the core of LCSA is the development of appropriate, quantitative, and practical indicators for all three major disciplines, E-LCA, LCC and S-LCA. Particularly, S-LCA indicators still pose fundamental challenges: they need to be empirically based (Kühnen and Hahn 2017), readily available and integrated into existing analytical structures (Hardadi and Pizzol 2017), yet also provide indication over positive and negative influence (Corona et al. 2017). These challenges are addressed in this special issue, but not all of them could be solved. Regardless, it is important to be present to the anthropogenic paradigm of LCSA, and to that end, the primary goals of sustainability and sustainable development. In the end, as Schaubroeck and Rugani (2017) suggest, human health and well-being, the heart and the minds of human existence is what we strive maintain. Or is there more?

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