Life Cycle Assessment: Past, Present, and Future †

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Life Cycle Assessment: Past, Present, and Future[†]

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Environmental life cycle assessment (LCA) has developed fast over the last three decades. Whereas LCA developed from merely energy analysis to a comprehensive environmental burden analysis in the 1970s, full-fledged life cycle impact assessment and life cycle costing models were introduced in the 1980s and 1990s, and social-LCA and particularly consequential LCA gained ground in the first decade of the 21st century. Many of the more recent developments were initiated to broaden traditional environmental LCA to a more comprehensive Life Cycle Sustainability Analysis (LCSA). Recently, a framework for LCSA was suggested linking life cycle sustainability questions to knowledge needed for addressing them, identifying available knowledge and related models, knowledge gaps, and defining research programs to fill these gaps. LCA is evolving into LCSA, which is a transdisciplinary integration framework of models rather than a model in itself. LCSA works with a plethora of disciplinary models and guides selecting the proper ones, given a specific sustainability question. Structuring, selecting, and making the plethora of disciplinary models practically available in relation to different types of life cycle sustainability questions is the main challenge.

Introduction

The study of environmental impacts of consumer products has a history that dates back to the 1960s and 1970s. Especially in a comparative context ("Is product A better than product B?"), it has spawned long and sometimes fierce debates (*1*). This is understandable, as alternative products typically have a number of distinguishing features. For instance, light bulbs of the fluorescent type have a longer life span and consume less energy than the traditional incandescent types, but they require more material and contain heavy metals. Other classic examples are baby diapers (paper versus cotton) and milk packaging (glass versus plastic versus carton).

It has been recognized that, for many of these products, a large share of the environmental impacts is not in the use of the product but in its production, transportation, or disposal. Gradually, the importance of addressing the life cycle of a product, or of several alternative products, became an issue in the 1980s and 1990s. Out of this emerged the idea of life cycle assessment (LCA), the "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" (*2*, *3*). In Figure 1, the emergence of this concept is illustrated by a literature count of LCA articles in ES&T.

Governments all over the world encourage the use of LCA. Increasingly, LCA has become a core element in environmental policy or in voluntary actions in the European Union, the USA, Japan, Korea, Canada, Australia and upcoming in booming economies as India and recently also China.

Along with the popularity of LCA came also its more creative use. We now see LCA studies on waste incineration, building materials, military systems, and tourism. Moreover, while the earlier studies were restricted to just a few environmental impact categories (such as cumulative energy use and solid waste), we now see an upspring of more intricate impacts (e.g., biodiversity and noise) and a broadening to economic and social impacts. Finally, we see an increase in the sophistication of the underlying models, from plain proportionality of activity-emission and emission-impact relations, to dynamic, regionalized, nonlinear models that include economic mechanisms, ecosystem restoration times, and more.

Altogether, we observe that LCA is booming in many directions: application, breadth, depth. In the present paper, we explore the main development in the context of past, present, and future. We start by describing the historical development of LCA and then proceed to discuss the developments of the past decade up to where we are now. We end by presenting results from a recent EU concerted action, the CALCAS project, which reviewed many of these developments.

The Past of LCA (1970−2000). In this section we will briefly discuss and evaluate LCA as developed and applied in the past, while distinguishing two periods: 1) 1970−1990 and 2) 1990−2000.

1970−1990: Decades of Conception. The first studies that are now recognized as (partial) LCAs date from the late 1960s and early 1970s, a period in which environmental issues like resource and energy efficiency, pollution control, and solid waste became issues of broad public concern (*4*). The scope of energy analyses (*5*−*7*), which had been conducted for several years, was later broadened to encompass resource requirements, emission loadings, and generated waste. One of the first (unfortunately unpublished) studies quantifying the resource requirements, emission loadings, and waste flows of different beverage containers was conducted by Midwest Research Institute (MRI) for the Coca Cola Company in 1969. A follow-up of this study conducted by the same institute for the U.S. Environmental Protection Agency in 1974 (*8*) and a similar study conducted by Basler & Hofman (*9*) in Switzerland marked the beginning of the development of LCA as we know it today. The MRI used the term Resource and Environmental Profile Analysis (REPA) for this kind of study, which was based on a systems analysis of the production chain of the investigated products "from cradle to grave". After a period of diminishing public interest in LCA and a number of unpublished studies, there has been

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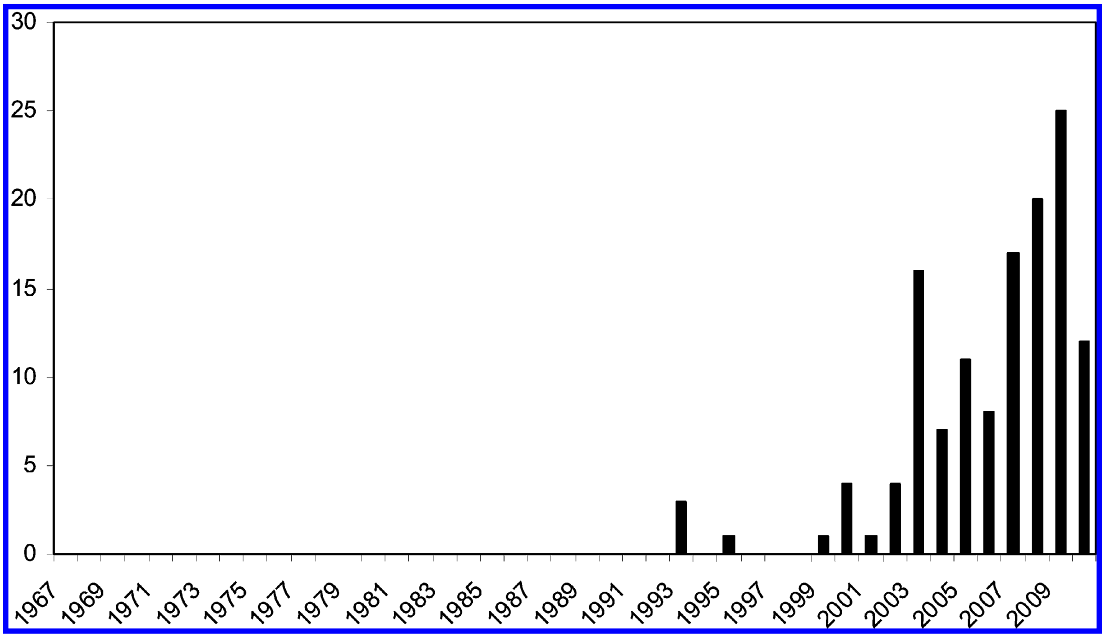

FIGURE 1. Histogram of the number of articles mentioning LCA in ES&T showing the emergence of LCA in particularly the 1990s, starting from the first issue of ES&T in 1967 (search on ACS Publication ES&T Web site on key word "LCA", accessed March 25, 2010).

rapidly growing interest in the subject from the early 1980s on. In 1984 the Swiss Federal Laboratories for Materials Testing and Research (EMPA) published a report (*10*) that presented a comprehensive list of the data needed for LCA studies, thus catalyzing a broader application of LCA (*4*). The study also introduced a first impact assessment method, dividing airborne and waterborne emissions by semipolitical standards for those emissions and aggregating them, respectively, into so-called "critical volumes" of air and "critical volumes" of water.

The period 1970–1990 comprised the decades of conception of LCA with widely diverging approaches, terminologies, and results. There was a clear lack of international scientific discussion and exchange platforms for LCA. During the 1970s and the 1980s LCAs were performed using different methods and without a common theoretical framework. LCA was repeatedly applied by firms to substantiate market claims. The obtained results differed greatly, even when the objects of the study were the same, which prevented LCA from becoming a more generally accepted and applied analytical tool (*11*).

1990–2000: Decade of Standardization. The 1990s saw a remarkable growth of scientific and coordination activities worldwide, which is reflected in the number of workshops and other forums that have been organized in this decade (*12–17*) and in the number LCA guides and handbooks produced (*18–25*). Also the first scientific journal papers started to appear in the Journal of Cleaner Production, in Resources, Conservation and Recycling, in the International Journal of LCA, in Environmental Science & Technology, in the Journal of Industrial Ecology, and in other journals.

Through its North American and European branches, the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role in bringing LCA practitioners, users, and scientists together to collaborate on the continuous improvement and harmonization of LCA framework, terminology and methodology. The SETAC "Code of Practice" (*26*) was one of the key results of this coordination process. Next to SETAC, the International Organization for Standardization (ISO) has been involved in LCA since 1994. Whereas SETAC working groups focused at development and harmonization of methods, ISO adopted the formal task of standardization of methods and procedures. There are currently two international standards:

- ISO 14040 (2006E): 'Environmental management - Life cycle assessment - Principles and framework' (*2*);
- ISO 14044 (2006E): 'Environmental management - Life cycle assessment - Requirements and guidelines' (*3*).

A key result of ISO's standardization work has been the definition of a general methodological framework (Figure 2).

The period of 1990–2000 can therefore be characterized as a period of *convergence* through SETAC's coordination and ISO's standardization activities, providing a standardized framework and terminology, and platform for debate and harmonization of LCA methods. In other words, the 1990s was a decade of standardization. Note, however, that ISO never aimed to standardize LCA methods in detail: "there is no single method for conducting LCA" (*2*).

During this period, LCA also became part of policy documents and legislation. The main focus was on packaging legislation, for example, in the EU (*27*) and the 1995 Packaging Law in Japan (*28*). Although LCA has proven its value in these policy-based applications, there were also problems with respect to the authoritativeness of results (cf. refs *29 and 30)*.

Several well-known life cycle impact assessment methods, still used today, evolved from methods developed in this period, such as the CML 1992 environmental theme approach (*21, 25*), end point or damage approaches (*31, 32*) but also the nowadays broadly accepted (*33, 34*) multimedia approach for assessing potentially human and ecotoxic emissions (*35*). Although this decade is mainly one of convergence, it is also the stage of scientific scrutiny, research into the foundations of LCA, and exploring the connections with existing disciplines. For instance, we observe sprouting ideas on consequential LCA and related allocation methods (*36–38*). These and other sophistications mark the transition to the present decade of LCA, which is not only a decade of elaboration but also of divergence in methods again.

The Present of LCA: Decade of Elaboration. The first decade of the 21st century has shown an ever increasing attention to LCA. In 2002, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched an International Life Cycle Partnership, known as the Life Cycle Initiative (*39*). The Life Cycle Initiative's main aim was formulated as putting life cycle thinking into practice and improving the supporting tools through better data and indicators. Life cycle

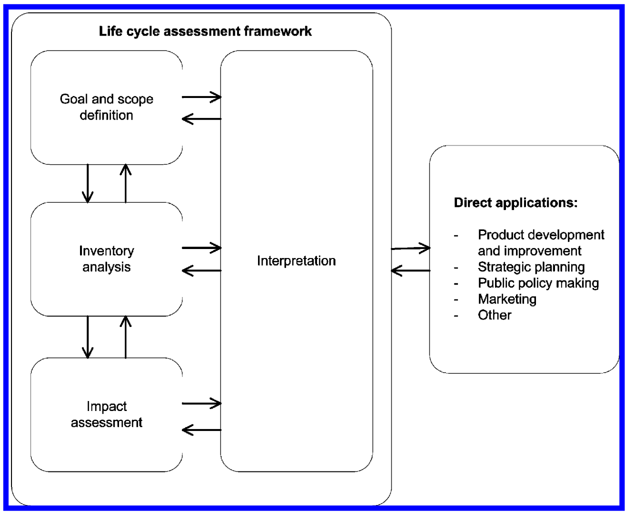

FIGURE 2. The general methodological framework for LCA (*2*).

thinking also continued to grow in importance in European Policy, as highlighted through, e.g., the Communication from the European Commission of the European Communities (CEC) on Integrated Product Policy (IPP (*40*)). On top of this, life cycle thinking was also incorporated in, e.g., the thematic strategies on the Sustainable Use of Resources (*41*) and on the Prevention and Recycling of Waste (*42*). In its 2003 Communication on Integrated Product Policy (IPP), the European Commission underlined the importance of life cycle assessment and the need for promoting the application of life cycle thinking among the stakeholders of IPP (*40*). In response, the European Platform on Life Cycle Assessment (*43*) was established in 2005, mandated to promote the availability, exchange, and use of quality-assured life cycle data, methods, and studies for reliable decision support in (EU) public policy and in business. In the USA, the U.S. Environmental Protection Agency started promoting the use of LCA (*44*). Various national LCA networks were also established like, for example, the large-scale Australian LCA Network (*45*) and the American Center for LCA (*46*), both in 2001, and the more small-scale Thai network (*47*) in 2000.

In this same period, environmental policy gets increasingly life-cycle based all over the world (e.g. refs *48 and 49*). For example, several life cycle-based carbon footprint standards have been, or are being, established (*50*). This standardization for environmental policy raised some severe problems, which have often not yet been solved adequately (*51*):

• As life-cycle based carbon footprint calculations may constitute the basis for e.g. granting subsidies to stimulate the use of bioenergy, it is of utmost importance that the indicator results be robust and 'lawsuit-proof'. This implies that the freedom of methodological choices for the handling of, e.g., biogenic carbon balances and allocation should be reduced to an absolute minimum (*52*).

• Another topic is that the limited scope of carbon footprints is not sufficiently accounted for when using the results. The scopes of carbon footprint studies can be limited in geographical coverage (dominated by Europe and North America), in feed stocks covered, in the number of different emissions to the environment included, and in environmental impacts addressed (carbon footprint studies are typically limited to global warming, while other environmental impacts can be more important when assessing the sustainability of, for example, biofuels: eutrophication, acidification, ecotoxicity and human toxicity, biodiversity, water use, etc. (*53*)). These limitations should at least be clearly reported as part of the conclusions of current, narrow-scope carbon footprint studies.

• A final topic of concern is the translation from functional-unit-based to real-world improvements. This may be the most difficult issue to address. Side-effects such as indirect land use, rebound effects, market mechanisms, and suchlike all play a role in how a large-scale production of biofuels would affect the food market, scarcity, social structure, land use, nature, and other things that are important for society. These are insufficiently addressed by current LCA studies, as was identified and analyzed by Sheehan (*54*), Voet and Lifset (*53*), and in the EU FP6 CALCAS project (*55*). Although consequential LCA (e.g., ref *56*) is very strong in mapping impacts of indirectly affected processes of a decision, modeling macroscopic land use changes on the basis of microscopic consequential product LCAs (bottom-up) is not likely to result in long-run sustainability. It may be more realistic to start thinking how more realistic, macroscopic scenarios for land use, water, resources and materials, and energy (top-down) such as drafted by the IPCC (*57*) and in the work by Graedel and van der Voet (*58*) can be transposed to microscopic LCA scenarios.

The period 2000−2010 can be characterized as the decade of elaboration. While the demand on LCA increases, the current period is characterized by a *divergence* in methods again. As ISO never aimed to standardize LCA methods in detail and as there is no common agreement on how to interpret some of the ISO requirements, diverging approaches have been developed with respect to system boundaries and allocation methods (*59, 60*), dynamic LCA (*61*−*64*), spatially differentiated LCA (*59, 60*), risk-based LCA (*65*−*68*), and environmental input-output based LCA (EIO-LCA) based and hybrid LCA (*69*−*71*) that may have a tense relation with some of the basic principles of the ISO standards. On top of this, life cycle costing (LCC; cf. ref *72*) - first used in the 1960s by the U.S. Department of Defense for the acquisition of high-cost military equipment (*73*) - and social life cycle assessment (SLCA; cf. ref *74*) approaches have been proposed and/or developed that may have consistency problems with environmental LCA in terms of system boundaries, time perspectives, calculation procedures, etc. (*75, 76*).

These different approaches have the life-cycle basis in common, but they differ in the methodological elaboration and in the question(s) they are addressing. We need to clarify exactly how the various approaches differ or overlap, but, most importantly, we need to clarify the link between questions and approaches: which approach is useful for which question. Despite new LCA textbooks being published (*77*−*79*), there is a further need for structuring this varying field of LCA approaches. We also need to take into account more types of externalities (economic and social impacts) and more mechanisms (rebound, behavior, price effects, dynamics) to meet the above-mentioned shortcomings of existing LCA studies in the field of, for example, biofuels while meeting specific user needs such as in simplified LCA.

The European Commission acknowledged this challenge and commissioned the CALCAS (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability) project in 2006 to structure the varying field of LCA approaches and to define research lines and programmes to further LCA where necessary. The CALCAS project has been finished and results have been published (*80*). One of its main results concerns the establishment of a framework for Life Cycle Sustainability Analysis (LCSA) linking life cycle sustainability questions to knowledge needed for addressing them, identifying available knowledge and related models, knowledge gaps and defining research programs to fill these gaps.

LCA Future (2010−2020): Decade of Life Cycle Sustainability Analysis. The LCSA framework is a framework for future LCA. It *broadens* the scope of current LCA from mainly environmental impacts only to covering all three dimensions of sustainability (people, planet, and prosperity). It also

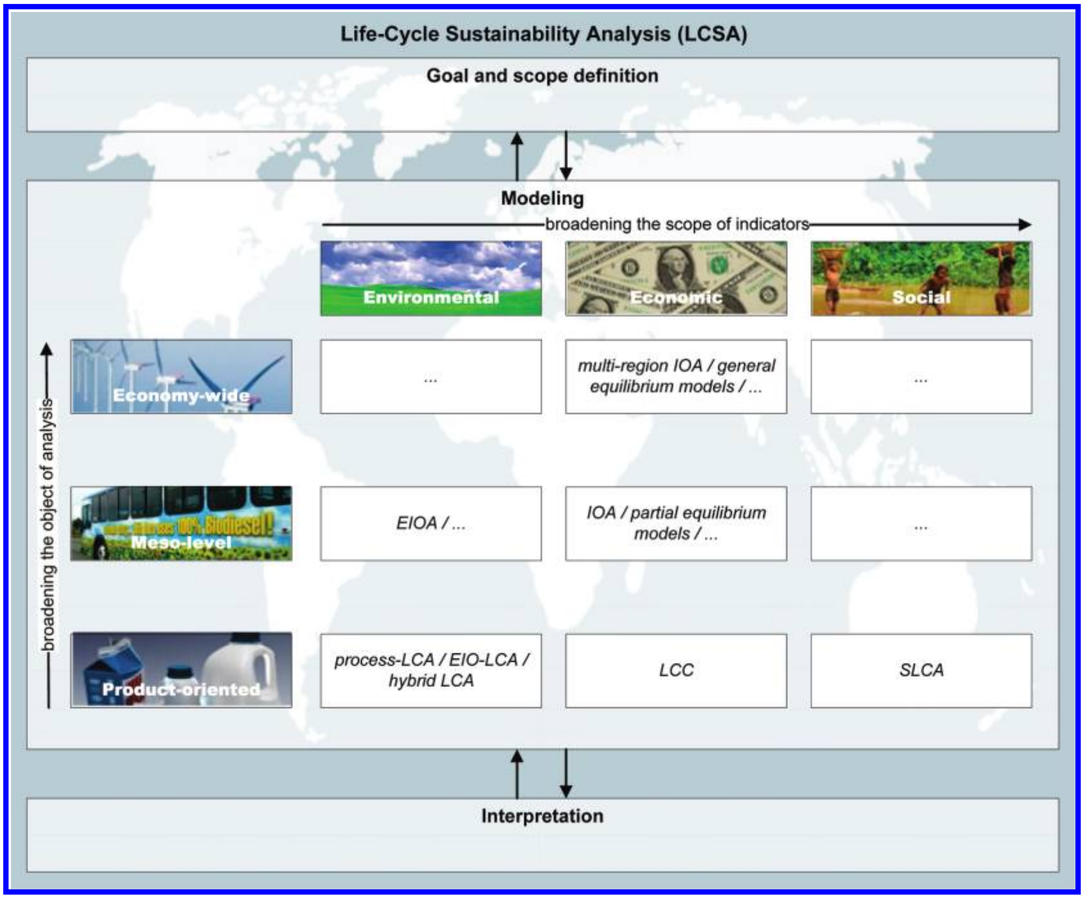

FIGURE 3. Transdisciplinary integration framework for life cycle sustainability analysis.

broadens the scope from predominantly product-related questions (product level) to questions related to sector (sector level) or even economy-wide levels (economy level). In addition, it *deepens* current LCA to also include other than just technological relations, e.g. physical relations (including limitations in available resources and land), economic and behavioral relations, etc. In addition as part of deepening, normative aspects such as discounting, weighting, and weak versus strong sustainability can be explicitly incorporated (*81*). The term framework is used as, unlike LCA, LCSA is a transdisciplinary integration framework of models rather than a model in itself. LCSA works with a plethora of disciplinary models and guides selecting the proper ones, given a specific sustainability question. Structuring, selecting, and making the plethora of models practically available in relation to different types of life cycle sustainability questions is then the main challenge. Although this is fully compatible with ISO's clause "there is no single method for conducting LCA", it is a significant deviation from LCA practice up until now. The broadening to economic and social impacts is also at variance with ISO's explicit restriction to environmental issues.

A schematic picture of the LCSA framework is provided in Figure 3 (adapted from ref *82*).

There are three important differences compared to the ISO 14040 framework of Figure 2:

1. The Merging of Inventory Analysis and Impact Assessment into One Modeling Phase (Middle Box). As has become clear during the past decade of academic work on agricultural production, climate change, impacts of land use, rebound, and so on, it is difficult to make a clear separation between behavior and technology and between technosphere and ecosphere. The fuel needed to drive 1 km with a certain car depends on the car, the drive style, the road, other traffic, and the traffic policy. Actual impacts of a seemingly technological process such as transportation are thus linked to consumer behavior, policy-making, strategic investments, etc. Some end point models like Eco-Indicator 99 (*32*) and ReCiPe (*83*) include human adaptation scenarios in their end point models on climate change, but they do not include the environmental implications of these adaption scenarios, such as the production of electricity to run additional air conditioners (as a consequence of global warming) or the production of additional sun blockers (as a consequence of ozone layer depletion).

2. The Broadening of the Object of Analysis (Vertical Arrow). Life cycle sustainability analysis can be performed at three different levels: product, meso, or economy. Products are thereby defined as in the ISO 14040 Standards and comprise any good or service. Product systems performing the same function(s) are compared, for example different options for milk packaging. Examples of methods and models for this level include process-LCA, EIO-LCA, hybrid LCA, life-cycle costing (LCC), and social LCA (SLCA). Meso refers to a level in-between product and economy-wide. It may include groups of related products and technologies, baskets of commodities (e.g., the product folio of a company), a municipality, a household, etc. An example at this level might be the introduction of biomass as a major car fuel. Defining and finding appropriate methods and models for this level needs further research (*84*) but may for example include environmental input-output analysis (EIOA), input-output analysis (IOA), and partial equilibrium models. Economy-wide refers both to economies of states or other geographical/political entities and eventually the world. An example question for this level might be the comparison of options for emerging technology domains, like for example large-scale introduction of wind energy or solar cells as strategy for phasing out fossil energy, nanotechnology, and new communication services. Defining and finding appropriate methods and models for this level also needs further research but may for example include IOA (*85*) and multiregion IOA (*86*). Obviously the three levels are not sharply defined, and there may be questions that fall somewhere in-between two levels.

3.The Broadening of the Scope of Indicators (Horizontal Arrow). Analyses are made for at least one set of sustainability indicators (environmental, economic, and/or social indicators). A distinction is made between life-cycle analyses with just one set of sustainability indicators (environmental, economic, or social) and Life-cycle Sustainability Analysis comprising of performance indicators for all three (or at least two) pillars of sustainable development (*86*).

The aspect of deepening is not shown in Figure 3. It mainly refers to the "Modeling" phase of LCSA. Deepening can be done in each box of the modeling phase. Consequential modeling is an example of deepening: it can be relevant and applied at each of the three levels of analysis and for each type of indicator. For a further discussion of the concept of deepening, we here refer to ref *82*.

Brief Examples. We here give three brief examples of how this framework could be applied and further developed in practice. The first example concerns a new design of a coffee machine. The company producing the coffee machine aims at improving its life cycle environmental performance, while its life cycle costs should not increase. For this, an ISO 144040/14044 based LCA study together with an LCC could be performed and that will generally suffice to support this designing decision.

The second example concerns a project that was recently carried out on the impact of diet changes in the EU (*87*). The question was whether a widespread switch to a Mediterranean diet would be environmentally beneficial. As the environmental burden from agriculture, and especially from livestock breeding, is known to be quite important, such an analysis was interesting for policy purposes. The study was a deepened as well as broadened LCA. First of all, it was an IO-based LCA, with consumer activities included. Next, it was based on the total consumption, not on an arbitrary functional unit. More fundamentally, it included the modeling of economic mechanisms insofar, that a shift in expenditure to buying additional products through the savings on food expenditures was modeled. Finally, economic restructuring of the agricultural sector was also included with a partial equilibrium model (*88*). For instance, meat producers that face a decreased domestic demand may respond by increasing export or by switching to alternative production structures.

A third example concerns a qualitative exercise that was performed as part of the CALCAS project (*83*) identifying the need for research to compare different options for Swedish production of biofuel to replace 25% of the fossil vehicle propellants in Sweden in the year 2030. Large-scale production of biofuel is likely to affect Swedish land-use. However, Sweden is part of an open global market, and a change in Swedish land-use is likely to affect exports and imports of other products from agriculture and/or forestry. This might affect the competition with land for food production, the cutting of tropical rainforests, etc. in other countries. Hence, the comparison might require a sustainability analysis of a global, economy-wide technosystem with all three sets of sustainability indicators, running land use models, food models, IO based LCA models, etc. From the starting question, we can derive more limited or specific questions at the product level (which biofuel is environmentally, economically, and/or socially benign), at the meso-level (how is the food-sector affected by the biofuel sector), and even at the economy-wide level (what are the physical limits of land use for food, biomaterial, and biofuel production). The details in the choice of questions determine all subsequent choices with respect to what objects of analysis, sustainability indicators, and models to include in the comparison and what decisions are supported by the comparison.

Discussion

LCA will be elaborated in many directions in the next decade. Regionalized databases will be developed, new impact assessment methods will be designed, and methods for uncertainty analysis will be improved, for example (*89*). These are obvious and important developments. However, more fundamentally, we believe that the second decade of the 21st century will be the decade of life cycle sustainability analysis. In this decade LCSA will hopefully develop offering a framework for questions at different levels of products, sectors, and economies and for addressing these questions to the full sustainability scope (people, planet, and prosperity) and to a more complete set of mechanisms.

Unlike LCA, LCSA rather is a framework of models than a model in itself: a transdisciplinary integration framework for disciplinary models and methods, selected and interlinked for addressing and answering a specific life cycle sustainability question. LCSA is a framework for looking from one viewpoint, i.e. the life cycle viewpoint, to sustainability questions and only providing life cycle answers and no other; risk assessment (RA) is, for example, not part of this framework. However, RA is very relevant for certain sustainability questions and should then be added to or performed instead of LCSA-tools.

LCSA shows similarities with the field of integrated assessment (IA). Sluijs (*90*) defines IA as "an interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole cause-effect chain of a problem can be evaluated [...]". As such, LCSA can be seen as the life-cycle incarnation of IA.

Establishing a framework for LCSA does not make present day product-oriented LCA and LCC superfluous. On the contrary, it only relates product-oriented LCA and LCC to specific questions, for which these specific methods are perfectly suitable.

One of the main challenges faced then is to structure and make available in a practical way the plethora of LCA and disciplinary models to various types of life cycle sustainability questions.

Making the LCSA framework operational for today's LCA practitioners, substantial research is needed. A map of this research has recently been published (*85*). The general scientific challenge is to derive consistent criteria for implementing methods in relation to specific life-cycle based questions. There is still a vast amount of research needed to achieve this, for example, in relation to the choice of attributional, consequential, and scenario-based modeling of systems and related time-frames, including aspects of unpredictability of emerging systems, complex adaptive systems, and other contingencies. In addition a new generation of ISO-type guidelines and LCSA handbooks would be valuable for consistently linking environmental, economic, and social disciplinary models to specific (categories of) questions.

Elaborating the LCSA framework is a major challenge for the global scientific community together with international governmental bodies: strong international collaboration is a must if we do not want to end up once more with a plethora of different approaches and methods!

Acknowledgments

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