Chapter 3
Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges?

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Abstract Environmental life cycle assessment (LCA) has developed fast over the last three decades. Today, LCA is widely applied and used as a tool for supporting policies and performance-based regulation, notably concerning bioenergy. Over the past decade, LCA has broadened to also include life cycle costing (LCC) and social LCA (SLCA), drawing on the three-pillar or 'triple bottom line' model of sustainability. With these developments, LCA has broadened from merely environmental assessment to a more comprehensive life cycle sustainability assessment (LCSA). LCSA has received increasing attention over the past years, while at the same time, its meaning and contents are not always sufficiently clear. In this chapter, we therefore addressed the question: what are LCSA practitioners actually doing in practice? We distinguished two sub-questions: which definition(s) do they adopt and what challenges do they face? To answer these questions, LCSA research published over the past half decade has been analysed, supplemented by a brief questionnaire to researchers and practitioners. This analysis revealed two main definitions of LCSA. Based on these two definitions, we distinguished three dimensions along which LCSA is expanding when compared to environmental LCA: (1) broadening of impacts, LCSA = LCA + LCC + SLCA; (2) broadening level of analysis, product-, sector- and economy-wide questions and analyses; and (3) deepening, including other than just technological relations, such as physical, economic and behavioural relations. From this analysis, it is clear that the vast majority of LCSA research so far has focused on the 'broadening of impacts' dimension. The challenges most frequently cited concern the need for more practical examples of LCSA, efficient ways of communicating LCSA results and the need for more data and methods particularly for SLCA indicators and comprehensive uncertainty assessment. We conclude that the three most crucial challenges to be addressed first are developing quantitative and practical indicators for SLCA, life cycle-based approaches to evaluate scenarios for sustainable futures and practical ways to deal with uncertainties and rebound effects.

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1 Introduction

Environmental life cycle assessment (LCA) has developed fast over the last three decades. The first studies that are now recognised 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. One of the first 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. Similar but independent studies were conducted in Europe by Sundström (1971) and by Basler and Hofman (1974). Together with several follow-ups, this marked the beginning of the development of LCA as we know it today (Guinée 1995; Hunt and Franklin 1996; Baumann and Tillman 2004; Guinée et al. 2011).

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. LCAs were performed using different methods and without a common theoretical framework. The obtained results differed greatly, even when the objects of the study were the same (Guinée et al. 1993).

The 1990s saw a remarkable growth of scientific and coordination activities worldwide, which among other things is reflected in the number of LCA guides and handbooks produced (ILV et al. 1991; Lindfors 1992; Grieshammer et al. 1991; Heijungs et al. 1992; Vigon et al. 1993; Lindfors et al. 1995; Curran 1996; Hauschild and Wenzel 1998). Also the first scientific journals appeared with LCA as their key topic or one of their main key topics. The period 1990–2000 showed convergence and harmonisation of methods through SETAC's coordination and ISO's standardisation activities, providing a standardised framework and terminology, and platforms for debate and harmonisation of LCA methods. During this period, LCA also became increasingly part of policy documents and legislation, particularly focusing on packaging. It is also the period that the scientific field of industrial ecology (IE) emerged, with life cycle thinking and LCA as one of its key tools (Graedel 1996; see Chap. 1).

The first decade of the twenty-first century has shown an ever-increasing attention to LCA resulting in new textbooks (e.g. Guinée et al. 2002; Baumann and Tillman 2004; EC 2010; Curran 2012; Klöpffer and Grahl 2014). LCA was increasingly used as a tool for supporting policies and (bioenergy) performance-based regulation. Life cycle-based carbon footprint standards were established worldwide in this period. During this period, LCA methods were elaborated in further detail, which unfortunately resulted in divergence in methods again. New approaches were developed with respect to system boundaries and allocation methods (e.g. consequential LCA; see also Chap. 2 of this book), dynamic LCA, spatially differentiated LCA, environmental input–output-based LCA (EIO-LCA) and hybrid LCA. On top of this, various life cycle costing (LCC) and social life cycle assessment (SLCA) approaches were proposed and/or developed. This broadening of environmental LCA to LCC and SLCA draws on the three-pillar (or triple bottom line, TBL) model of sustainability, distinguishing environmental, economic and social impacts of product systems along their life cycle. The original conception of LCA only dealt with the environmental or ecological component, whereas with these latter developments, LCA broadened itself from a merely environmental LCA to a more comprehensive life cycle sustainability assessment (LCSA).[1] This broadening is consistent with developments in IE, for which sustainability and the three-pillar model are principal motivations (Allenby 1999; Graedel and Allenby 1999).

As a matter of course, a subject section was formed within the International Society for Industrial Ecology (ISIE) in 2011, to focus on life cycle assessment (LCA) as currently existing and on life cycle sustainability analysis (LCSA) as a direction in which LCA was developing. Meanwhile several journals have opened up special sections on LCSA, clearly confirming that we are in the middle of the ‘LCSA age’.

While several researchers have proposed definitions and methods for LCSA over the past recent years, many practitioners are still left in confusion on what LCSA exactly is, what its methods are and when to apply what. An interesting question therefore is what are LCSA practitioners doing in practice? We distinguished two sub-questions:

- Which definition(s) do they adopt?
- What challenges do they face?

In this chapter, these questions will be addressed by first discussing two different definitions of LCSA and the interpretations of sustainability that these definitions are grounded in and then analysing the LCSA research published over the past half decade replenished by inputs from members of the ISIE-LCSA section[2] on adopted definitions of LCSA and main challenges faced. We will conclude with our top three of the main challenges.[3]

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[1] Sometimes LCSA is taken as life cycle sustainability analysis. For a discussion on the different reasons for adopting assessment or analysis, we here refer to Zamagni et al. (2009) and Sala et al. (2013b). Here we adopt assessment to stay close to the ISO definition of LCA.

[2] In order to learn what exactly the understanding of LCSA is by members of the ISIE-LCSA section, a questionnaire was issued. All members were invited through the section’s electronic platform and through e-mail invitations to provide their views on:

1. Their (preferred) definition of life cycle sustainability assessment
2. Their top three of (scientific and/or practical) challenges for LCSA

Seventeen people reacted on this invitation and their inputs are gratefully used below.

[3] Note that this does not imply that there are no other challenges; it just reflects the author’s top three.

2 Definitions of LCSA

Definitions of LCSA are not yet carved in a stone. The first use of the term LCSA was by Zhou et al. (2007), but they only addressed climate change and resource depletion impacts in their LCA and combined it with an LCC, which doesn't fully comply with the three-pillar model. Shortly after Zhou et al. (2007), Klöpffer and Renner (2007; see also Klöpffer 2008) provided a definition of LCSA, and later on, Guinée et al. (2011) built on that definition. Thus today, at least two definitions of LCSA exist:

- Klöpffer and Renner (2007; see also Klöpffer 2008): 'Given the widespread acceptance of the [triple bottom line] model, it is rather straightforward to propose the following scheme for Life Cycle Sustainability Assessment (LCSA): LCSA = LCA + LCC + SLCA, where LCA is the SETAC/ISO environmental Life Cycle Assessment, LCC is an LCA-type ('environmental') Life Cycle Costing assessment and SLCA stands for societal or social Life Cycle Assessment'. According to this definition, LCSA thus broadens ISO-LCA to also include economic and social aspects adopting a life cycle approach. Klöpffer (2003) already argued for combining LCA with LCC and SLCA, but he did not use the term LCSA at that time. As mentioned by Klöpffer and Renner, this TBL-based life cycle approach was earlier introduced by the German Oeko-Institut in a method called 'Produktlinienanalyse' in 1987 (Projektgruppe ökologische Wirtschaft 1987).
- Guinée et al. (2011): LCSA links '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. […] 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 *broadens* the object (or level) of analysis 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 behavioural relations, etc. […] LCSA is a trans-disciplinary *framework* for integration 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'.

Guinée et al. (2011) basically adopted the definition by Klöpffer and Renner (2007) but added two dimensions and called it a framework rather than a method in itself. Based on these two definitions, we can thus distinguish between three dimensions along which LCSA expands when compared to (environmental) LCA:

1. Broadening of impacts: LCSA = LCA + LCC + SLCA
2. Broadening level of analysis: product-, sector- and economy-wide questions and analyses

3. Deepening: including other than just technological relations, such as physical, economic and behavioural relations

To better understand the different LCSA definitions above, we need to discuss the interpretations of ‘sustainability’ that the different definitions of LCSA are grounded in.

3 Sustainability

As mentioned above, the Projektgruppe ökologische Wirtschaft (1987) firstly introduced a life cycle approach including all three dimensions of sustainability. The year of publication of their ‘Produktlinienanalyse’ coincided with the year of publication of the Brundtland report ‘Our Common Future’ (WCED 1987). The Projektgruppe ökologische Wirtschaft obviously did not yet use the term ‘sustainability’.

Klöpffer (2008; English version of Klöpffer and Renner (2007); see also Klöpffer (2003)) extensively discusses what exactly they mean by LCSA. They adopted the ‘triple bottom line’ (Elkington 1998) or the ‘three-pillar’ interpretation of sustainability, referred to as ‘people, planet and prosperity’ at the World Summit on Sustainable Development in Johannesburg in 2002. The triple bottom line approach basically says that for achieving more sustainable futures, environmental, economic as well as social impacts of activities have to be taken into account. In the World Summit on Sustainable Development in Johannesburg in 2002, also life cycle analysis (http://www.un-documents.net/jburgpln.htm) was introduced, and thus, Klöpffer (2003) argues that ‘any environmental, economic, or social assessment method for products has to take into account the full life cycle from raw material extraction, production to use and recycling or waste disposal. In other words, a systems approach has to be taken’. The background for the LCSA definition by Klöpffer (2008) and Klöpffer and Renner (2007) is thus the ‘triple bottom line’ or ‘three-pillar’ interpretation of sustainability, which is a very common interpretation (e.g. Mitchell et al. 2004; Blewitt 2008) adopting a system approach.

The Guinée et al. (2011) LCSA framework is based on the work done as part of the EU FP6 CALCAS (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability) project (http://www.calcasproject.net/). The interpretation of sustainability is similar to Klöpffer (2008) and Klöpffer and Renner (2007), but two additions were made: broadening of the level of analysis and deepening the analysis itself. The rationales behind these two additions originate from:

(a) An analysis of the bioenergy debate and the role of LCA in this debate (Zamagni et al. 2009)
(b) The simple observation that although huge efforts have been made to improve the environmental performance of products applying LCA, little or no progress has been made improving the environmental sustainability of the global economy as a whole (Rockström et al. 2009; EPA2013; PBL 2013)

The bioenergy debate showed that LCAs may show some fundamental flaws when applied as a tool for supporting bioenergy performance-based regulation (PBR). We distinguish between flaws related to differences in methods applied between studies (e.g. related to attributional vs. consequential analysis, data sources, gaps and uncertainties, choices of functional unit, allocation method, impact categories and characterisation method) and flaws in impacts and mechanisms considered for the systems analysed. For PBRs, LCA results should be robust and 'lawsuit proof', implying that the freedom of methodological choices for the handling of such issues as biogenic carbon balances and allocation should be reduced to an absolute minimum, uncertainties should be properly dealt with and it should be realised that there may be a gap between the translation of results based on a functional unit of a litre of biofuel to real-world improvements for millions of litres. There are huge differences between LCA studies on bioenergy systems as identified by Voet et al. (2010). Besides these methodological differences, most of these LCA studies have been limited to considering only environmental impacts and not taking into account system effects and consequences such as indirect land use, rebound effects and market mechanisms. These all play a role in how a large-scale production of bioenergy could affect the food market, scarcity, social structure, land use, nature and other conditions that are important for society. Large-scale policies to stimulate bioethanol in the USA and Europe have led to consequences which were not really foreseen and were barely considered in the preparatory LCA-type studies (Zamagni et al. 2009). A framework for deepened analysis – including more of these mechanisms – was lacking so far.

The fact that we may improve the environmental performance of products while still increasing the global pressure on the environment implies that we cannot simply focus on single product systems only, but also have to broaden our life cycle-based analyses to baskets of products, sectors and whole economies. Referring to the well-known IPAT equation (Ehrlich and Holdren 1971), which decomposes environmental impact (I) into the separate effects of population size (P), affluence (A) and technology (T), LCAs so far have focused on the pollution per functional unit of product or service. This basically is no more than a 'supermicro' analysis of T. If the total consumption of products and services (increasing affluence) and the size of the population keep increasing meanwhile, we may not achieve any improvement in (macro) global sustainability despite significant progresses in (micro) sustainability of (a number of) individual products and services.

Both these arguments resulted in the LCSA definition by Guinée et al. (2011) which added two dimensions to the definition by Klöpffer (2008) and Klöpffer and Renner (2007).

4 LCSA Definitions Adopted in Practice

In order to find out which definition of LCSA practitioners adopt in practice, a bibliometric analysis was carried out of the ISI Web of Science (WoS) published by Thomson Reuters. The keywords used under 'topic' for searching 'all databases' were ‘life cycle sustainability assessment*’ OR ‘life cycle sustainability analys*’ for the time span = 2000–2014 (accessed on 24/11/2014). The result of this bibliometric analysis is shown in Table 3.1. References basically covering the same topic and originating from the same research institute were grouped together. For example, Heijungs et al. (2010), Guinée and Heijungs (2011) and Guinée et al. (2011) basically cover the same topic (presenting an LCSA framework covering all three dimensions of the LCSA definition) and originate from the same research institute (CML). In addition, references that despite the use of LCSA had little or no connection to LCSA and the two questions posed here were eliminated from the results. Put more precisely, a reference was excluded from further analysis if it could not comply with one or more of the following criteria:

- The term LCSA was used to refer to one of the two (revised or otherwise) definitions of LCSA discussed above.
- If the reference focused on broadening of impacts, it should include analyses of all three pillars (e.g. LCA + LCC + SLCA).
- If the reference focused on broadening of the level of analysis and/or deepening the analysis, it should do so as part of LCSA.

The resulting (groups of) references were then analysed on their coverage of the three dimensions mentioned above (see also Table 3.1).

The bibliometric analysis resulted in about 30 articles covering the topic of LCSA (Table 3.1). Table 3.1 shows that almost all of the LCSA studies published so far focus on the ‘broadening of impacts’ dimension: LCSA = LCA + LCC + SLCA. Among these studies are many case studies. In addition, explorations have been made to widen the scope of the three pillars to include, for example, cultural aspects (Pizzirani et al. 2014). Along a similar line, Jørgensen et al. (2013) argue that when fully adopting the WCED (1987) definition of sustainability, LCA and SLCA in particular ‘should be expanded to better cover how product life cycles affect poverty and produced capital’. Only a few studies report on the ‘broadening of the level of analysis’ and/or ‘deepening’ dimensions; most of these studies are reviews or methodological by nature.

The main keywords popping up among the ISIE-LCSA membership from the response concerning the question on their preferred definition of LCSA are ‘environmental-social-economic’ besides ‘product’, ‘sustainability’ and ‘assessment’.

From both the bibliometric analysis and the brief questionnaire, it becomes obvious that the vast majority of LCSA articles have focused on the ‘broadening of impacts’ dimension: LCSA = LCA + LCC + SLCA. However, this may rather be a limitation of our bibliometric analysis since we only searched for articles including the terms life cycle sustainability assessment(s) or life cycle sustainability analysis(es), while many articles in the ‘broadening of the level of analysis’ (like IOA) and ‘deepening’ (like rebound modelling and uncertainty analysis) domains may not use these terms in their topical descriptions. This immediately touches upon a problem of too encompassing or too strict definitions: the Guinée et al. (2011) definition of LCSA includes broadening of the level of analysis and deepen-

Table 3.1 LCSA references as a result from the bibliometric analysis of the Thomson Reuters ISI Web of Science (WoS) databases on 'life cycle sustainability assessment*' OR 'life cycle sustainability analys*' for the time span = 2000–2014 (accessed on 24/11/2014), classified on their coverage of the three dimensions of LCSA

References	Case (C) or methodology/review (M) study	Broadening impacts	Broadening analysis	Deepening
Klöpffer (2008) and Klöpffer and Renner (2007)	M	Y	N	N
Finkbeiner et al.(2010)	C	Y	N	N
Moriizumi et al. (2010)	C	Y	N	N
Heijungs et al. (2010), Guinée and Heijungs (2011), and Guinée et al. (2011)	M	Y	Y	Y
Halog and Manik (2011)	M/C	Y	Y	Y
Manzardo et al. (2012)	M	Y	N	N
Menikpura et al. (2012)	C	Y	N	N
Stamford and Azapagic (2012)	C	Y	N	N
Traverso et al. (2012a, b)	M/C	Y	N	N
Zamagni (2012)	M	Y	Y	Y
Bachmann (2013)	M	Y	N	N
Cinelli et al. (2013)	M[a]	Y	Y	Y
Giesen et al. (2013)	M	Y	Y	Y
Hu et al. (2013)	M/C	Y	Y	Y
Jørgensen et al. (2013)	M	Y	N	N
Kucukvar and Tatari (2013)	C	Y	N	N
Pesonen and Horn (2013)	M	Y	N	N
Sala et al. (2013a, b)	M	Y	Y	Y
Vinyes et al. (2013)	C	Y	N	N
Zamagni et al. (2013)	M	Y	Y	Y
Onat et al. (2014) and Kucukvar et al. (2014a, b)	C	Y	Y	N
Ostermeyer et al. (2013)	C	Y	N	N
Stefanova et al. (2014)	M/C	Y	Y	Y
Heijungs et al. (2014)	C/M	N	Y	Y

Y Yes, *N* No

[a] This reference is a workshop report

ing, while research in these dimensions is often developed as specific approaches rather than topics under the umbrella of LCSA.

5 Main Challenges Identified in LCSA Studies So Far

The references in Table 3.1 were then analysed on the challenges faced. In Annex 1, these challenges are summarised for the different (groups of) references. Scanning through these references and generalising the challenges identified results in the following interpretation of the main challenges:

- The need for data and methods, particularly the lack of (proper and quantitative) SLCA indicators (Klöpffer 2008; Finkbeiner et al. 2010; Traverso et al. 2012a; Hu et al. 2013; Ostermeyer et al. 2013; Kucukvar and Tatari 2013; Vinyes et al. 2013; Zamagni et al. 2013).
- The need for practical (case study) examples (how to put LCSA in practice?) (Cinelli et al. 2013; Giesen et al.. 2013; Hu et al. 2013; Zamagni et al. 2013).
- How to communicate LCSA results (Finkbeiner et al. 2010; Traverso et al. 2012a, b; Bachmann 2013; Pesonen and Horn 2013)?
- The need for comprehensive methods dealing with all relevant uncertainties related to life cycle-based approaches (Zamagni 2012; Pesonen and Horn 2013; Kucukvar and Tatari 2013 and Kucukvar et al. 2014a, b).
- How to deal with technological, economic and political mechanisms at different levels of analysis (Cinelli et al. 2013; Sala et al. 2013a, b; Zamagni 2012; Zamagni et al. 2013)?
- The need for more dynamic models (Ostermeyer et al. 2013; Onat et al. 2014).
- How to deal with value choices and subjectivity in, particularly, the weighting step (Stamford and Azapagic 2012; Traverso et al. 2012b; Bachmann 2013; Manzardo et al. 2012; Sala et al. 2013a, b; Vinyes et al. 2013)?
- The need for further development of life cycle-based scenario evaluations (Zamagni 2012; Heijungs et al. 2014).
- How to deal with benefits (beneficial impacts), particularly in SLCA (Bachmann 2013)?
- How to avoid double counting (inconsistent application) between LCA, LCC and SLCA (Zamagni 2012; Bachmann 2013)?
- How to deal with different perspectives (producer, customer, societal) on costs in LCC (Finkbeiner et al. 2010)?
- How to (practically) relate (disciplinary) models to different types of life cycle sustainability questions (Guinée et al. 2011; Zamagni et al. 2013; Stefanova et al. 2014)?

From this list of challenges, those most frequently cited concern the ‘broadening of impacts’ dimension in general, the need for more practical examples of LCSA, efficient ways of communicating LCSA results and the need for more data and methods particularly for SLCA indicators and comprehensive uncertainty assessment. Note that with respect to SLCA, there are many more authors that identified these challenges (e.g. Jørgensen et al. 2008), but their references were excluded due to the limitations of our bibliometric analysis (see above).

The number of indicators that the various studies adopt for addressing the three pillars of sustainability in a life cycle perspective varies from a few (e.g. Moriizumi et al. limit their LCSA of two mangrove management systems in Thailand to just three indicators, one for each dimension of the 'triple bottom line') to several dozen indicators (e.g. Stamford and Azapagic adopted 43 indicators to address the same three pillars in their LCSA on electricity options for the UK). The challenges faced by studies adopting only a few indicators obviously include how to broaden the number of indicators. The challenges for studies adopting dozens of indicators include how to communicate their results to decision-makers and/or how to further weight (evaluate) and aggregate the indicator results, for example, applying (multi-criteria) decision analysis.

The topic of 'deepening' is addressed less by the studies listed in Annex 1. Nevertheless, several references mention (e.g. Cinelli et al. 2013; Sala et al. 2013b; Zamagni 2012; Zamagni et al. 2013; Pesonen and Horn 2013; Kucukvar and Tatari 2013; Kucukvar et al. 2014a, b) and some even address (Hertwich et al. 2014) typical 'deepening' topics such as the need for comprehensive uncertainty assessment and methods for dealing with rebound effects. But, again, these references were excluded from Table 3.1 and Annex 1 due to the limitations of our bibliometric analysis (see above). However, we feel that deepening discussions are very important as part of maturing LCSA approaches. We illustrate this by the example of modelling rebound effects in a life cycle perspective, which has been addressed by several authors (Hertwich 2005; Hofstetter et al. 2006; Thiesen et al. 2008; Girod et al. 2011; Druckman et al. 2011; Font Vivanco and Voet 2014).

Hertwich (2005) defines the rebound effect as 'a behavioural or other systemic response to a measure taken to reduce environmental impacts that offsets the effect of the measure. As a result of this secondary effect, the environmental benefits of eco-efficiency measures are lower than anticipated (rebound) or even negative (backfire)'. For example, the positive effect of more efficient cars has largely been offset by an overall shift to larger and heavier cars (see Chap. 18). Similarly, the introduction of high-efficient light bulbs has been combined with an expansion of the number of light points. Recently, Font Vivanco and Voet (2014) performed a review describing the state of the art in incorporating the rebound effect into LCA-based studies and analysed their main strengths and weaknesses. Their literature review identified a total of 42 relevant scientific documents, from which 17 provided quantitative estimates of the rebound effect using LCA-based approaches. It appeared that 'the inclusion of the rebound effect into LCA-based studies is still one of the most relevant unresolved issues in the field; […] only few studies provide quantitative estimates (mostly for carbon dioxide and global warming […])'. Font Vivanco and Voet concluded that 'while a number of LCA-based studies have considered such effects […], no generally applicable guidelines have been developed so far; […] consequently, a panoply of non-consensual definitions and analytical approaches have arisen within the LCA community, and rebound effects have been both unevenly and inconsistently incorporated into LCA-based studies'. The results of this reviews show that, while incorporating the rebound effect into LCA studies is recognised as a very important topic and has received some attention, there is still no generally applicable and/or comprehensive method for dealing with rebound in a life cycle perspective. A similar conclusion is valid with respect to the challenge of incorporating comprehensive though practical uncertainty assessments into LCA (see, e.g. Gregory et al. 2013; Harst and Potting, 2013; Henriksson et al. 2014, 2015; Mendoza et al. 2014).

Finally, the bibliographic analysis showed that there are an increasing number of LCSA studies (e.g. Giesen et al. 2013; Hu et al. 2013; Manzardo et al. 2012; Stefanova et al. 2014; Heijungs et al. 2014) dealing with scenarios.[4] The studies explore possible configurations of emerging new technologies, product systems or consumption baskets, comparing their potential impacts to alternative technologies, product systems and consumption baskets. Such studies are very relevant, particularly if performed ex ante or parallel to the technology development trajectory, as in that way LCSA is able to advise the technology developer whether developments are on the 'right' track while identifying hot spots for improvement. Considering this increase and the relevance of scenarios for evaluating possible more sustainable futures, we might even consider changing the meaning of the abbreviation LCSA from life cycle sustainability assessment to life cycle-based scenario assessment.

The results from our brief questionnaire among the ISIE-LCSA membership largely support the challenges discussed above while particularly adding challenges as communication with and involvement of stakeholders in the LCSA process, education and standardisation of LCSA methods.

6 Conclusions

Adopting the Guinée et al. (2011) definition of LCSA while not underestimating other challenges, we see the following challenges as crucial to address first (one challenge for each dimension of LCSA):

1. *Broadening of impacts*: proper, preferably quantitative and practical indicators for SLCA.
2. *Broadening the level of analysis*: develop, implement and apply life cycle-based approaches to evaluate scenarios for sustainable futures.
3. *Deepening*: develop and implement ways to deal with uncertainties and rebound effects as comprehensively and practically as possible.

The challenge to develop proper, preferably quantitative and practical, indicators for SLCA has been present ever since SLCA was proposed as a possible approach.

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[4] See also Spielmann et al. (2005), Hertwich et al. (2014) and Koning et al. (2015) that report on scenario-based life cycle modelling but not as part of an LCSA framework. See also Chap. 2 of this book.

Many proposals have been developed in this area (see Jørgensen et al. 2008), but the range of methods proposed and developed differs widely. They also often face implementation problems. The bottom line is that there is not at present ‘anything resembling an agreed approach or methodology’ (Clift 2014). Most efforts so far have focused on finding and developing ways to include social impacts using impact categories and indicators, similar to environmental LCA. Considering the challenges identified in Annex 1 and the period over which discussions on SLCA’s challenges have continued, one may wonder ‘whether it is really appropriate to model social LCA on environmental LCA’ and whether or not ‘Social LCA is more likely to develop as a useful tool if it is not forced into the mould of environmental LCA’ (Clift 2014). This is not a new discussion since Udo de Haes (see Klöpffer 2008) already argued in 2008 that ‘social indicators do not fit in the structure of LCA’ because developing ‘a quantitative relationship of the indicator to the functional unit’ or properly handling the high spatial dependency of the indicator is problematic when trying to squeeze such impacts into environmental LCA. To prevent progress on SLCA coming to a dead end, fundamental re-examination of SLCA’s paradigm seems necessary eventually leading to increased applicability and a more comprehensive coverage of social benefits and impacts of life cycles. Since a platform for this discussion seems to be lacking, the ISIE-LCSA section could offer this.

Life cycle-based approaches have an important role to play in assessing scenarios on how to feed, fuel and fibre about nine billion people – all longing for the ‘good’ life – in a sustainable way in 2050 (cf. Frosch and Gallopoulos 1989). We need to develop approaches and tools within the LCSA framework for evaluating the sustainability of scenarios for such a future. One of the sub-challenges is to make sensible and proper use of the different modes of LCA and LCSA available. The key challenge is to effectively combine backcasting LCSA[5] (BLCSA; Heijungs et al. 2014) with forecasting LCSA (FLCSA) approaches (e.g. Hertwich et al. 2014; Koning et al. 2015) and eventually also product LCA (CLCA as well as ALCA) in such a way that policies and transitions towards a more sustainable future can be properly supported and monitored.[6]

All our life cycle tools should be accompanied with proper ways of dealing with uncertainties of data, methodological choices, assumptions and scenarios and pref-

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[5] Heijungs et al. (2014) defined backcasting LCSA as exploring ways, in a life cycle perspective, to stay within normatively defined sustainability levels (e.g. planetary boundaries) through adapted affluence, population growth and/or technologies.

[6] Note that we make a distinction between supporting policy *development* and monitoring *developed* policies. It’s our belief that we need different tools for supporting policy development (e.g. CLCA; see also Chap. 2 of this book) and for monitoring accepted policy (e.g. ALCA for monitoring bioenergy performance-based regulation through carbon footprint studies). For policy development, we need to analyse all possible direct and indirect consequences of potential policy options using life cycle-based scenario analysis for which CLCA, BLCSA, FLCSA and other scenario-based life cycle approaches (e.g. Spielmann et al. 2005; Hertwich et al. 2014; Koning et al. 2015) are best suited. For monitoring existing, accepted policies, we need clear black and white answers and no scenario-based ranges of answers; for this, ALCA seems better suited.

erably also with proper ways of handling rebound effects. This is particularly important since the results of our tools are increasingly supporting public policies and performance-based regulations. However, most of our studies still present their results as point values, suggesting that life cycle tools produce black and white results with no uncertainties while all experienced practitioners of these tools know better than this. Thus, in order to maintain and increase the credibility of our life cycle decision-support tools, we need to develop, as a matter of priority, approaches to properly and transparently deal with uncertainties associated with data, models, choices and assumptions of all life cycle-based methods (LCA, LCC, SLCA, IOA, hybrid LCA, etc.). Several methods have been proposed for this (see above), but the main remaining challenge is to harmonise them to be comprehensive (e.g. covering all types of uncertainty for all phases of LCA in a common approach, covering all types of rebound effects for complete life cycles in a common approach) and implement them (through, e.g. data and software tools) in the daily practice of practitioners. Similar reasoning is valid for rebound effects.

Finally, as mentioned above, one of the sub-challenges is to make sensible and proper use of the different modes of LCA and LCSA available. For LCA and LCSA, we currently have at least the following modes of analysis at our disposal: attributional (ALCA/ALCSA), backcasting (BLCA/BLCSA), consequential (CLCA/CLCSA), decision or dynamic (DLCA/DLCSA), exergy (ELCA/ELCSA) and potentially resulting in A–Z LCA/LCSA. We should thus pay due attention to relating sustainability questions to the most appropriate tools of our industrial ecology toolbox. The alternative is to throw the dic

e.

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Annex 1: Challenges Faced in the LCSA References from the Bibliometric Analysis

References	Short topic description	Challenges faced
Klöpffer (2008) and Klöpffer and Renner (2007)	Discussion of possible definitions for LCSA of products	Quantitative methods needed for decision-making if different solutions are offered; quantification difficult challenge for SLCA
Finkbeiner et al.(2010)	The 'life cycle sustainability dashboard' and the 'life cycle sustainability triangle' are presented as examples for communication tools for both experts and non-expert stakeholders	Real and substantial implementation of the sustainability concept
		Comprehensive, yet understandable presentation of LCSA results
		Different possible perspectives (producer, customer, societal) when considering the life cycle costs
		Data availability
		To unambiguously determine and measure sustainability performance for processes and products
		Trade-off between validity and applicability
Moriizumi et al. (2010)	To assess the sustainability of two mangrove management systems in Thailand using a life cycle approach and using three indicators: net global warming emissions (CO_2-eq.; environmental indicator), amount of employment created in local communities (social indicator) and the value of cash flow generated (economic indicator)	Other environmental indicators; estimation of spillover impacts of production activity; combining the results with decision-support tools

Heijungs et al. (2010), Guinée and Heijungs (2011), and Guinée et al. (2011)	Proposal of a framework for LCSA	Structuring, selecting and making the plethora of disciplinary models practically available in relation to different types of life cycle sustainability questions
		To derive consistent criteria for implementing methods (e.g. attributional, consequential and scenario-based modelling of systems and related time frames, including aspects of unpredictability of emerging systems, complex adaptive systems, etc.)
		LCSA research methods and practical examples
		Linking approaches to questions
		Backcasting LCA
Halog and Manik (2011)	Integrated methodology for LCSA by capitalising the complementary strengths of different methods used by industrial ecologists and biophysical economists	n.a.
Manzardo et al. (2012)	To develop a 'grey-based' group decision-making methodology for the selection of the best renewable energy technology using an LCSA (LCA + LCC + SLCA) perspective and addressing the issue of uncertainty	Subjectivity involved in qualitative evaluations
Menikpura et al. (2012)	Development of a method for comprehensive sustainability assessment on most of the critical environmental, economic and social impacts starting from LCA	n.a.
Stamford and Azapagic (2012)	To identify the most sustainable options for the future UK electricity mix applying a sustainability assessment framework developed previously by the same authors	The influence of priorities and preferences of different stakeholders on the outcomes of the sustainability assessment of electricity options
Traverso et al. (2012a)	The integration of LCSA and the dashboard of sustainability into a so-called life cycle sustainability dashboard (LCSD) and its first application to a group of hard floor coverings	Having (quantitative) data for the (particularly SLCA) indicators considered
		How to handle qualitative data that can particularly be meaningful in the social assessment, in a basically quantitative method

(continued)

References	Short topic description	Challenges faced
Traverso et al. (2012b)	Application of life cycle sustainability assessment (LCSA) and the life cycle sustainability dashboard (LCSD) for comparing different PV modules	Selection of social LCA indicators
		Weighting sets needed for the LCSD
		More case studies needed, for example, to calibrate indicators and weights
Zamagni (2012)	Editorial on a new section on LCSA	How can the LCSA framework be consistently applied, considering different degrees of maturity of LCA, LCC and SLCA?
		Is adopting the same system boundary for LCA, LCC and SLCA always feasible and conceptually correct?
		What role does scenario modelling play in the LCSA framework?
		What approaches exist for including mechanisms in the analysis?
		How can different domains, normative positions (values) and empirical knowledge be dealt with?
		How can future changing structures of the economy be accounted for?
		How can uncertainty be accommodated and managed?
Bachmann (2013)	Ranking of power generation technologies by means of (1) the total cost approach, adding private and external costs, and (2) a multi-criteria decision analysis (MCDA) integrating social, economic and environmental criteria	How to separate the different life cycle-based assessments into environmental, economic or social in particular to avoid double counting?
		The inclusion of risks
		Dealing with benefits
		Dealing with value choices
Cinelli et al. (2013)	Workshop on LCSA: the state-of-the-art and research needs – November 26, 2012, Copenhagen, Denmark	How to communicate LCSA results?
		How to put LCSA into practice?
		Dealing with technological, economic, political relations at different scales of analysis
		Theoretical roots of LCSA and frameworks

Giesen et al. (2013) and Hu et al. (2013)	Putting the LCSA framework of Guinée et al. (2011) into practice by five operational steps: (1) broad system definition, (2) making scenarios, (3) defining sub-questions for individual tools, (4) application of the tools and (5) interpreting the results in an LCSA framework	How can LCSA be approached practically?
		Only one social impact indicator could be modelled in the process-based LCA structure
		More case study examples needed
Pesonen and Horn (2013)	Streamlined rapid assessment tool – the sustainability SWOT – and empirical testing of its impact on the corporate world analysing whether or not it leads changes in either strategic or operative-level activities	Development of approaches to quicken the resource-consuming inventory and assessment phases of LCSA; easy-to-understand communication of results; streamlined approach for managing uncertainties of all types with transparency and competence
Sala et al. (2013a, b)	Review of main challenges posed to sustainability assessment methodologies and related methods in terms of ontology, epistemology and methodology of sustainability science	A framework for SA should be able to better deal with externalities, interrelations, different applications, multiple stakeholder needs and multiplicity of legitimate perspectives of stakeholders, to deal with nonlinearities, normative choices, uncertainties and risks
		LCSA should be developed ([further] in order to:
		Guarantee a holistic perspective in the assessment
		Be hierarchically different from LCA, eLCC and sLCA. It should represent the holistic approach integrating (and not substituting) the reductionist approach of the single part of the analysis
		Enhance transparency and scientific robustness
		Tailor the assessment for local/specific impact
		Encourage and systematise the interaction among stakeholders involved in the
		development, application and use of the LCSA results
		Widen the goal of the integrated assessment (e.g. including not only negative but also positive impacts)

(continued)

References	Short topic description	Challenges faced
Vinyes et al. (2013)	LCSA comparison of three domestic collection systems for used cooking oil (UCO) to determine which systems should be promoted for the collection of UCO in cities in Mediterranean countries	Quantitative indicators for SLCA
		Relating social indicators/impacts to the functional unit
		How to restrict social indicators proposed to a manageable and comparable number
		Weighting methods
Zamagni et al. (2013)	From LCA to LCSA: concept, practice and future directions. Introductory article to a special issue on LCSA	Limited number of LCSA applications, the majority of which focus on the interface of environmental and economic aspects; social aspects are less addressed
		SLCA data and indicators
		Weak understanding at the conceptual level of SLCA and LCSA
		What is the appropriate scale of LCSA: products, enterprises, communities or nations?
Kucukvar and Tatari (2013)	To quantify the overall environmental, economic and social impacts of the US construction sectors using an economic input–output-based sustainability assessment framework	Lack of comprehensive data sets for all three pillars
		Uncertainty assessment
Onat et al. (2014)	Integrating several social and economic indicators demonstrating the usefulness of IO modelling for quantifying sustainability impacts, providing an economy-wide analysis and a macro-level LCSA	Dynamic system approach
Kucukvar et al. (2014b)	To develop a triple bottom line sustainability assessment model evaluating the environmental and socio-economic impacts of pavements	Uncertainty assessment; weighting of different impacts
Kucukvar et al. (2014a)	Adding fuzzy multi-criteria decision-making method to the approach above	Uncertainty of LCA results including weighting of sustainability indicators and limitation of the EIO method should be included in decision-making

Ostermayer et al. (2013)	The application and potential of LCSA in the built environment, focusing on refurbishment of residential buildings, LCA, LCC and limited social assessment, and applying a multidimensional Pareto optimisation method	Dynamic modelling of energy mixes and related LCI data sets; dynamic modelling of discount rates and energy price scenarios for LCC; suitable indicators for SLCAs
		Extreme dependence and differentiation of SLCA indicators on regional and cultural conditions; lack of data for SLCA; discussion needed on what aspects need to be implemented into SLCA at least
Stefanova et al. (2014)	An approach to structure the goal and scope phase of LCSA to identify the relevant mechanisms [deepening] to be further modelled for a case study on a new technology for the production of high-purity hydrogen from biomass to be used in automotive fuel cells	Structured identification of [deepening] mechanisms to be modelled in a specific case
Heijungs et al. (2014)	Using IO tables, planetary boundaries and minimum consumption levels to backcast directions to ‘safe operating spaces’	Improving the backcasting models to including more impact categories, dynamics, definition of a welfare function, allocation of surplus consumption to consumption categories, etc.

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