sustainability

Review

Review of Sustainability Assessment Approaches Based on Life Cycles

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Abstract: Many different approaches have been developed to quantify and evaluate sustainability. Here a review is performed on sustainability assessment based on Life Cycle Thinking, which mostly means Life Cycle Sustainability Assessment (LCSA). Until the end of 2018, 258 publications can be found, from which 146 include a case study. The highest number of publications appeared between 2016 and 2018 and, compared to the years before 2016, the number of authors has increased. However, in recent years the focus has been more on case studies than on methodological aspects of LCSA. The presented holistic approaches for LCSA are either too broad or too narrow for scientific guidance. Therefore, many questions concerning LCSA are still open, e.g., regarding definition of sustainability dimensions and the desire or need for multi-criteria decision-analysis. An underlying problem is the lack of discussion about sustainability concepts. The momentum in the community to perform case studies for LCSA should be used to also develop more guiding principles.

Keywords: life cycle sustainability assessment; life cycle assessment; life cycle costing; social life cycle assessment; review

1. Introduction

The assessment of sustainability is a subject that is often discussed. Many different approaches have been developed to quantify and evaluate sustainability [1]. Concepts that integrate three dimensions of sustainability, i.e., environment, economy and society, have spread widely (cf. [2]). A possible methodology to assess sustainability based on this concept is Life Cycle Sustainability Assessment (LCSA), which derives from Life Cycle Thinking. This approach means that a system, e.g., a product, a service or an organization, is considered from cradle to grave. The different dimensions of sustainability have already been assessed according to this concept for several decades with the help of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and social Life Cycle Assessment (S-LCA) [3]. For the development of LCSA, the publications by Klöpffer et al. [4–7] were most important. They highlighted the importance of understanding that a product's lifecycle consists of different systems, namely: raw material extraction, production, use of the product and its disposal [4]. Crucially, the author argues that this approach enables the identification and avoidance of "trade-offs" in impacts between different systems and the shifting of impacts between different time periods. They have demanded the combination of the assessment of the different sustainability dimensions. This has led to the approach

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{S-LCA}$$

The guidance document on LCSA by the UNEP/SETAC [8] is followed. In this document LCSA is described as the " . . . evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" [8].

Having this approach in mind, practitioners have studied many different technologies. All dimensions of sustainability are discussed in relation to biomass-related systems. This includes biofuels [9–18], woody biomass [19], and agri-food systems [20–22]. Other technologies featured in discussions of sustainability and LCSA aspects are: energy systems [23,24], nanomaterials [25], polymer products [26], the process of sustainable manufacturing [27,28], and retrofitting of buildings [29]. LCSA is also discussed in relation to certain aspects, e.g., product design [30], intellectual capital statement in enterprises [31], sustainability assessment for companies [32], Life Cycle Management [33], or regional development [34]. In addition, a comparison between different approaches of assessing circular economy (LCSA vs. cradle to cradle) has been performed [35]. Besides these classical subjects for Life Cycle Thinking, LCSA is discussed with respect to very different subjects, e.g., cultural heritage [36–38], or the choice of impact categories based on safeguard subjects [39].

As LCSA is about combining different methods with each other, integrating more complex modeling frameworks has also been considered, e.g., multi-criteria assessment with Computational Systems Modelling Framework [40] or agent based modelling [41]. An overview of suitable methods connected to LCSA is given by Eason, et al. [42]. All three main assessment methods, i.e., LCA, LCC, S-LCA, are based on the ISO 14040 framework [43,44]. Therefore, LCSA follows this framework, too. This includes the four phases Goal and Scope Definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation.

Still, the methodological development is an important part of the LCSA discourse [45,46]. In their publication Sala, et al. [47] have evaluated existing LCSA approaches and are in favor of a more holistic procedure, which might also address general or complex system theory and post-normal science. As part of an EU-project Minkov, et al. [48] have summarized the current status of LCSA and have identified future research needs in the methodological development of LCC and S-LCA. Minkov, et al. [48] state that S-LCA encompasses the social and socio-economic impacts associated with the product and that these can be classified into both stakeholder and impact categories. In relation to the social component, the specific actors that are affected are given greater consideration. They foster further case studies to overcome these issues by learning-by-doing. More elaborated is the contribution of Guinée [49] to the discussion of the methodological development of LCSA based on the analysis of LCSA publications and a brief questionnaire to researchers and practitioners. As a conclusion, he identifies three major topics that need to be addressed in the future: (a) The development of quantitative and practical indicators for S-LCA, (b) approaches to assess scenarios from a life cycle perspective, and (c) more standardized methods to include uncertainties and rebound effects.

Another type of publication regarding LCSA are reviews of other LCSA publications. An initial attempt at this topic made Hannouf and Assefa [50] with their presentation giving a rough overview of applied methods and result presentation strategies. They found major research demand regarding synergies and trade-offs between the three dimensions of sustainability. In addition, reviews with special foci have been published. Tarne, et al. [51] have evaluated the existing approaches for LCSA to be adopted for the automotive industry, identifying three aspects with further research needs, namely (a) consistent execution of the three assessment methods, (b) low maturity of S-LCA, and (c) adequate presentation and interpretation of results. De Luca, et al. [52] have concentrated on agricultural management and the usage of multi-criteria decision-analysis (MCDA) for decision making based on LCSA. In the authors' opinion, MCDA can "deal with subjective assumptions in an objective way, to take into consideration actors' values and to overcome trade-offs among the different dimensions of sustainability". Onat, et al. [53] discuss LCSA publications and highlight the benefits of multiregional Input–Output models as part of integrated modelling for global LCSA and of assessing the dependency of impact categories as well as occurrence of rebound effects. Therefore, the authors foster a harmonization of tools, methods and disciplines related to LCSA. The most recent review by Costa, et al. [54] gives a very good overview of recent publications and the different applied methods. The authors show not only the temporal development but also the geographical distribution of the publications. By doing so, they found out that the discussion is very strongly based on Europe and that, in the former years, Germany in particular played a significant role in the development of LCSA. These already existing reviews on LCSA still leave out many aspects, e.g., the role of bigger groups and projects on the development of LCSA, sustainability issues, and the structured evaluation of different assessment methods in LCSA.

Against this background, it is the aim of this paper to review the existing LCSA case studies first regarding their goal and scope definition. Goal and Scope Definition is an important phase of an LCSA, because it is at this stage that many aspects influencing the results are fixed. This also means that for a review of this phase many aspects have to be discussed. The second part of this review is based on the usage of LCA, LCC, and S-LCA in the publications. Subsequent multi-criteria decision-analysis or normalization, aggregation and weighting are optional steps. Within an LCSA, however, the guidance of the analysis through a vast volume of results becomes even more important. Therefore, the analysis here gives special attention to this third topic (Figure 1). These analyses on different methods in LCSA are accompanied by the evaluation of recent developments in LCSA. Therefore, first of all a short insight into the temporal development of LCSA is given before the materials and methods of the current review are presented.

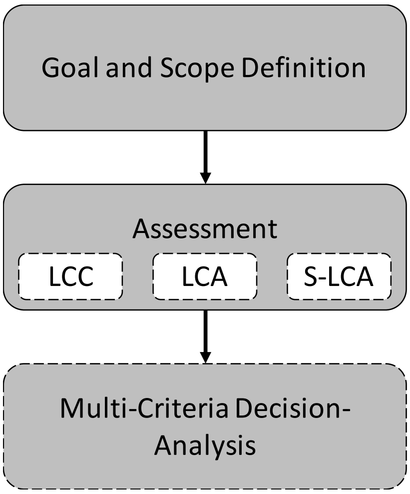

Figure 1. Analyzed steps of Life Cycle Sustainability Assessment (LCSA) within this review. LCC: Life Cycle Costing; S-LCA: social Life Cycle Assessment; LCA: Life Cycle Assessment.

1.1. Temporal Development of LCSA

In 1987 Öko-Institut introduced a methodology for analyzing all dimensions of sustainability on a life cycle basis (called *Produktlinienanalyse*) [55]. Since 2007 a revised version of this methodology is also available in English (Product Sustainability Assessment PROSA [56]). In 1995, the Social and Environmental Life Cycle Assessment (SELCA) [57] was introduced to combine LCA with the social dimension of sustainability. Three years later, in 1998, the integration of the economic dimension was discussed [58]. However, the issue of LCSA did not gain momentum until Klöpffer published his articles about linking LCA, LCC, and S-LCA [4–7] (see Figure 2). The first so-called Life Cycle Sustainability Assessment was done in 2007 [59] although only economic and environmental indicators were assessed. Since then an increasing number of methodology papers and case studies were published. In 2011 the UNEP/SETAC Life Cycle Initiative published a guidance document about how to realize an LCSA [8].

As first company, BASF published their approach called SEEbalance in 2005 to assess the sustainability of products [60]. Although other companies see LCSA as part of their life cycle management (LCM) [61] and some even take part in the scientific debate to a small extent [62] most of these approaches are only used internally and are not published scientifically. An overview about methods applied in industry for sustainability assessment is given by Saurat, et al. [63].

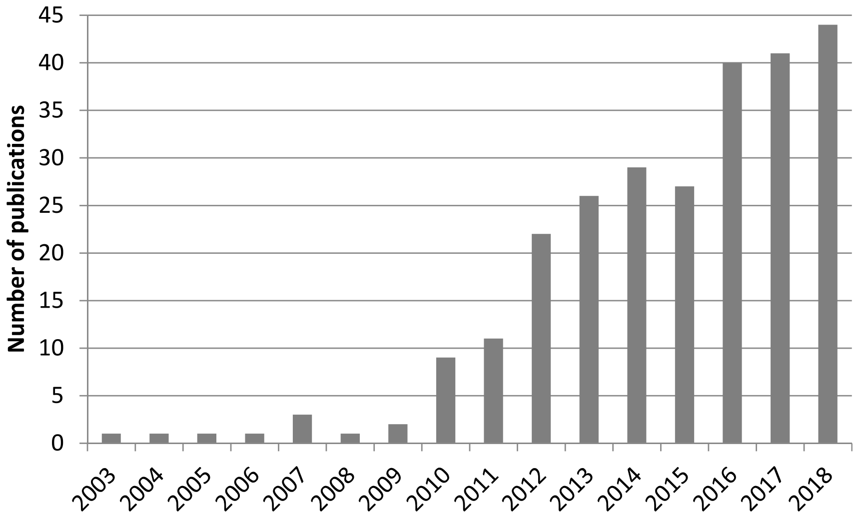

Figure 2. Overview of the chronological distributions of Life Cycle Sustainability Assessment (LCSA) publications until end of 2018.

1.2. Materials and Methods

This review covers publications, i.e., peer-reviewed papers, project reports, PhD theses, conference papers and book chapters, until the end of 2018, which were at least available online. Up to this date, 258 publications were found. Keywords for the selection were "Life Cycle Sustainability Assessment" or "Life Cycle Sustainability Analysis", which are often used as synonyms [64] though they might imply a difference in methodology. The researched sustainability assessments were required to cover environmental, economic and social impact categories. Furthermore, a life cycle perspective had to be applied for the assessments. Moreover, publications implementing Life Cycle Thinking and three dimensional assessments but which do not call themselves Life Cycle Sustainability Assessment, e.g., PROSA [56], are analyzed in this paper. The increase of publications over the years is shown in Figure 2. Before 2003, only one publication [55] was published in the field of sustainability assessment from a life cycle perspective on the level of process chains. After 2003, interest in the concept of LCSA was aroused and since 2009 it is growing rapidly. In 2016, a boost in publications occurred compared to the former years and the number remained at this level for the following years.

Of 258 publications, 146 complement methodological considerations with a case study to illustrate their approach. These case studies are analyzed in detail for this review. An overview of these studies is given in Table 1. If several studies are written by the same working group, e.g., University of Central Florida, or if the same methodological approach is used, e.g., CALCAS (Co-ordination action for innovation in Life Cycle Analysis for Sustainability), they are clustered in the table. Within each cluster, single studies are ordered by their year of publication. For each study, information about the number of analyzed indicators for the three sustainability dimensions (environment, costing, social) as well as the dimension of technology (indicators for efficiency etc.) is listed. The classification whether a certain indicator belongs to the environmental, economic or social dimension is adopted from the respective studies. This means, for instance, that the indicator human toxicity is in one study considered as an environmental indicator and in another study as a social indicator. Furthermore, for the environmental indicators it is stated whether the LCA is carried out on a midpoint or an endpoint level. Another important topic for LCSA is the optional normalization, weighting and aggregation of the indicator results. This tabular overview gives a short introduction to whether a study uses normalization and aggregation and what normalization method is used. In addition, the technology analyzed in the case study is stated. The temporal development of the different working groups is very well illustrated in this table. In the former years, only few groups were working on LCSA, e.g., TU Berlin. Since 2016, however, more papers from new authors are published, while less is published by the early movers.

Table 1. In detail analyzed LCSA studies.

References	Year	Analyzed Indicators					Normalization	Aggregation	Case Study
		Environment		Costing	Social	Tech			
		#	m/e	#	#	#			
University of Manchester									
Stamford and Azapagic [65]	2011	11	m	5	19	6	No	No	Nuclear energy
Stamford [66]	2012	8	m	3	8	3	No	No	Electricity generation in UK
Amienyo [67]	2012	12	m	2	16	-	No	No	UK beverage sector
Stamford and Azapagic [68]	2012	11	m	7	19	6	No	No	Electricity generation in UK 2025
Ibáñez-Forés, et al. [69]	2013 2014	6	m	4	2	1	Min–max	No	Best available technology
Santoyo-Castelazo and Azapagic [70]	2014	10	m	3	10	-	Ranking	Yes	UK Energy system
Stamford and Azapagic [71]	2014	10	m	5	14	7	Ranking	Yes	UK Energy system 2070
Sims [72]	2014	12	m	4	9	9	Max	Yes	Heating systems in the UK
Atilgan and Azapagic [73]	2016	11	m	3	6	-	?	Yes	Electricity generation in Turkey
Azapagic, et al. [74]	2016	10	m	5	14	7	Yes	Yes	UK energy system 2070 [g]
Galán-Martín, et al. [75]	2016	9	m	3	6	-	Yes	Yes	Electricity technologies in the UK
Atilgan and Azapagic [76]	2017	11	m	3	5	-	Yes	Yes	Turkey energy system 2050
Cooper [77]	2017	11	m	3	14	-	Min–max multiple	Yes	Shale gas in the UK
Kouloumpis and Azapagic [78]	2018	6	m	3	3	-	Min–max	Yes	Electricity generation in UK 2025
University of Central Florida									
Kucukvar and Tatari [79]	2013	8	m	3	3	-	No	No	US Building sector
Kucukvar, et al. [80]	2014	10	m	63	-	-	Topsis	Pavements	
Kucukvar, et al. [81]	2014	10	m	2	4	-	Max	Yes	Pavements
Onat, et al. [82]	2014	10	m	4	5	-	Max	No	Alternative passenger vehicles
Onat, et al. [83]	2014	10	m	2	3	-	Yes (?)	No	US Building sector
Noori, et al. [84]	2015	4	m	2	3	-	Yes (?)	Yes	Wind power plants
Tatari, et al. [85]	2015	6	m	7	4	-	No	No	Buildings [e]
Onat, et al. [86]	2016	5	-	4	6	-	Topsis	Yes	Alternative vehicle technologies
Onat, et al. [87]	2016	9	m	3	4	-	Max	Yes	Alternative passenger vehicles
Onat, et al. [88]	2016	2	m	2	3	-	No	No	Alternative passenger vehicles
Gumus, et al. [89]	2016	4	m	5	-	Topsis	Yes	U.S. wind energy	
Onat, et al. [90]	2016	3	m	2	2	-	No	No	Alternative passenger vehicles

Table 1. *Cont.*

		Analyzed Indicators							
References	**Year**	**Environment**		**Costing**	**Social**	**Tech**	**Normalization**	**Aggregation**	**Case Study**
		#	**m/e**	**#**	**#**	**#**			
TU Berlin									
Schau, et al. [91]	2012	12	m	5–6	?	-	Min–max	Yes	Remanufactured alternators
Traverso, et al. [92]	2012	11	e	6	19	-	Min–max	Yes	Photovoltaic modules
Traverso, et al. [93]	2012	6	m	6	6	-	Min–max	Yes	Natural hard floor coverings
Chang, et al. [94]	2012	18	m	2	12	-	No	No	Bamboo bicycle
Lehmann [95]	2013	10	m	2	71	-	No	No	Indonesian water supply
Martínez-Blanco, et al. [96]/Martínez Blanco [97]	2014/2012	11	m	3	12–23	-	No	No	Fertilizer
Buchert, et al. [98]	2015	3	m	2	1	-	No	No	Bamboo bicycle
Neugebauer [99]	2016	1	m	1	1	-	No	No	Tomato growing, pedelec frames, modular machine tool frames
Stark, et al. [100]	2017	1	m	1	1	-	No	No	Pedelec
Ren									
Ren, et al. [101]	2015	4	m	1	3	-	Min–max	Yes	Chinese bioethanol
Ren, et al. [102]	2016	2	m	5	3	4	PROMETHEE	Yes	Hydrogen production
Ren, et al. [103,104]	2017	3	m	3	2	1	Min–max	Yes	Energy and industrial systems
Ren and Liang [105]	2017	4	-	2	2	3	max	yes	Alternative marine fuels
Ren [106]	2018	4	m	3	3	-	Min–max	yes	Alternatives for electricity generation in UK ^{k}
Ren [107]	2018	4	m	3	3	-	Min–max	yes	Alternatives for electricity generation in UK ^{k}
Ren, et al. [108]	2018	6	m	4	4	-	max	yes	Alternatives for electricity generation in UK ^{k}
Ren and Toniolo [109]	2018	2	m	1	4	3	Min–max	yes	Hydrogen production
Ochoa Bique and Zondervan [110]	2018	2	-	3	4	-	Min–max	yes	Urban sludge treatment
Seebalance									
Saling, et al. [60]	2005	11	m	?	?	-	External	Yes	Benzene, aniline
Kölsch [111]	2010	11	m	1	22	-	External	Yes	Chemicals
Shiau and Chuang [112]	2012	5	m	4	13	-	Max	Yes	Gravel transport
Ausberg, et al. [113]	2015	11	m	1	17	-	External	Yes	Acetanisole

Table 1. *Cont.*

		Analyzed Indicators							
References	**Year**	**Environment**		**Costing**	**Social**	**Tech**	**Normalization**	**Aggregation**	**Case Study**
		#	**m/e**	**#**	**#**	**#**			
King Mongkut's University of Technology									
Gheewala, et al. [114]	2011	1	m	1	1	-	No	No	Biorefinery Complex in Thailand
Sadamichi, et al. [115]	2012	1	m	1	1	-	No	No	Biomass Utilization for Energy in East Asian Countries
Menikpura, et al. [116]	2012	2 [c]	m	1	2 [c]	-	No [e]	No [c]	Municipal solid waste management systems
Menikpura, et al. [117]	2013	2	e	1	2	-	No	No	Municipal solid waste management
ILCSA									
Rettenmaier, et al. [118]	2014	16	m	13	5	6	Benchmark	No	Sorghum, bioethanol Biorefinery
Müller-Lindenlauf, et al. [119]	2014	13	m	6	10	3	Benchmark	No	Biorefinery
Keller, et al. [120]	2015	13	m	13	5	6	Benchmark	No	Biorefinery
Halog									
Halog and Manik [121]	2011	16	m	4	15	-	?	Yes	Biofuels Supply Chain.
Yu and Halog [122]	2015	10	m	10	24	-	Yes (?)	No	Australian photovoltaic
Luu and Halog [123]/Luu and Halog [124]	2016	3	e	3	7	-	External	Yes	Vietnamese electricity generation [h]
Halog and Manik [125]	2016	4	m	2	24	-	?	Yes	Palm oil biodiesel [h]
Forschungszentrum Jülich STE									
Wulf, et al. [126]	2017	11	m	2	15	-	Ranking Min–max Min Min–max	Yes	Rare earth permanent magnets
Hake, et al. [127]	2017	11	m	5	23	-	Min–max	Yes	Alkaline water electrolysis
Wulf, et al. [128]	2018	15	m	4	24	-	No	No	Alkaline water electrolysis
CALCAS									
Hu, et al. [129]	2013	-	m/e	-	-	-	No	No	Concrete recycling
Stefanova, et al. [130]	2014	-	-	-	-	-	No	No	Hydrogen from biomass
Environmental Performance Strategy Map									
De Benedetto and Klemeš [131]	2009	4	m	1	9	-	External	Yes	Pesticides
De Benedetto and Klemeš [132]	2015	4	m	1	9	-	External	Yes	Pesticides

Table 1. *Cont.*

References	Year	Analyzed Indicators					Normalization	Aggregation	Case Study
		Environment		Costing	Social	Tech			
		#	m/e	#	#	#			
LInX									
Khan, et al. [133]	2004	11	m	3	3	4	Min–max	Yes	Electricity production
Bailey, et al. [134]	2010	11	m	3	3	4	Min–max	Yes	Biogas plant
University of Hong Kong									
Dong [135]	2014	14 + 3	m/e	2	13	-	Min–max	Yes	Building construction
Dong and Ng [136]	2016	14 + 3	m/e	7	13	-	No	No	Building construction
DLR									
Weiss, et al. [137]	2011	8	m	2	2	-	Topsis	Yes	Aircraft
Weiss, et al. [138]	2012	9	m	2	2	-	Topsis	Yes	Aircraft
Ostfold Research									
Valente, et al. [139]	2013	5	m	4	12	-	No	No	Norwegian Biorefinery [e]
Valente [140]	2014	4	m	1	5	-	No	No	Chestnuts in Piedmont region
Shanghai Jiao Tong University									
Jin and Borthwick [141]	2016	6	m	1	1	-	No	No	Biogas production
Jin, et al. [142]	2017	7	m	2	?	-	No	No	Biogas production
IFSUL									
Zortea [143]	2013	7	m	4	9	-	Min–max	Yes	Biodiesel production [e]
Zortea et al. (2018)	2018	3	m	3	9	-	Min-Max	Yes	Soybean production
PROSA									
Grießhammer, et al. [56]	2007	5	m	6	10 [a]	-	External Min–max	Yes	Products
ToSIA									
Lindner, et al. [144]	2010	3	m	1	2	-	No	No	Forest-wood-chains
Prosuite									
Blok, et al. [145]	2013	26[b]	e	3	11	-	External	Yes	Nanotechnology, Biorefineries, Carbon Capture and Storage, Multifunctional mobile devices
Other									
May and Brennan [146]	2006	12	m	5	4	-	No	No	Australian electricity generation
Zhou, et al. [59]	2007	2	m	1	0	1	Min–max	Yes	Fuels
Moriizumi, et al. [147]	2010	1	m	1	1	-	No	No	Mangrove plantation management

Table 1. *Cont.*

References	Year	Analyzed Indicators					Normalization	Aggregation	Case Study
		Environment		Costing	Social	Tech			
		#	m/e	#	#	#			
Dobon, et al. [148]	2011	10	e	2	1	-	No	Yes	Packaging concepts for food
You, et al. [149]	2012	1	m	1	1	-	No	No	Bioethanol production
Nzila [150]/Nzila, et al. [151]	2012	3	m	3 [l]		3	Max	No	Biogas Production in Kenya
Lloyd, et al. [152]	2012	2+2	m/e	1	1	-	Max	No	Lightweighting material
Foolmaun and Ramjeawon [153]	2013	7	e	1	10	-	Ranking	Yes	Mauritian PET-bottle disposal
Vinyes, et al. [154]	2013	11	m	1	8	-	Max	Yes	Used cooking oil waste management
Ostermeyer, et al. [155]	2013	13	m	1	?	-	Min–max	No	Building refurbishment
Rochat, et al. [156]	2013	4	e	1	1	-	External	Yes	Recycling of PET waste
Khalili, et al. [157]	2013	5	m	5	5	6	No	Yes	Cigarette butt litter in tobacco industry [e]
Souza, et al. [158]	2013	3	m/e	3	3	1	No	No	Brazilian Waste Electric and Electronic Equipment [e]
Luthe, et al. [159]	2013	1	m	1 [e]	4 [e]	-	No	No	Skies
Busset, et al. [160,161]	2014	20	m/e	1	2	1	No	No	Virgin olive oil production
Hacatoglu [162]	2014	12	m	2	0	5	Benchmark	Yes	Hybrid energy systems
Lu, et al. [163]	2014	11	e	5	4	-	No	No	Reuse of waste mobile phones
Maxim [164]	2014	2	m	1	4	-	Min–max	Yes	Electricity generation technologies
Mjörnell, et al. [165]	2014	2	m	2	[d]	-	Min–max	Yes	Renovation alternatives
Pastare, et al. [166]	2014	4	m/e	3	2	3	Topsis	Yes	Macro-algae for biogas Production
Akhtar, et al. [167]	2015	5	m/e	3	0	-	?/External	Yes	Sewer pipe materials
De Luca, et al. [168]	2015	5	m	4	3	-	No	No	Agriculture systems [e]
Hossaini, et al. [169]	2015	12	m	1	5	-	Yes	Yes	Buildings
Suwelack and Wüst [170]	2015	3	m	2	2	-	Min–max	Yes	Biomass conversion systems (test data)
Hirschberg and Burgherr [171]	2015	11	m/e	9	16	-	Min–max	Yes	Energy generation technologies
Li, et al. [172]	2015	4	m	1	2	-	AHP	Yes	Municipal solid waste management
Aziz, et al. [173]	2016	5	m	2	6	-	External	Yes	Composting in Thailand
Maier, et al. [174]	2016	11	m	6	19	4	Ranking	Yes	Cooking Stoves in Bangladesh
Sou, et al. [175]	2016	15	m	1	1	1	Yes	Yes	Bottom ash disposal
Touceda [176]/Touceda, et al. [177]	2016	2	m/e	2	2	-	No	No	Household refurbishment
van Kempen, et al. [178]	2016	2	e	1	3	-	No	No	Kitchen set
Pizzirani, et al. [38]	2016	14 [e]	m	7 [e]	6 [e]	7 [i]	No	No	Forest management

Table 1. *Cont.*

References	Year	Analyzed Indicators					Normalization	Aggregation	Case Study
		Environment		Costing	Social	Tech			
		#	m/e	#	#	#			
Huang and Mauerhofer [179]	2016	3	m	1	1	-	No	No	Ground source heat pump
Choi, et al. [180]	2016	5	m	1	2	-	No	No	Highway Concrete Rehabilitation
Gencturk, et al. [181]	2016	10	m	10	10 (1) ^{f}	-	External	Yes	Reinforced concrete buildings subjected to earthquakes
Kalbar, et al. [182]	2016	3	m	1	3	5	Topsis	Yes	Waste water treatment alternatives
Lolli, et al. [183]	2016	17	m	1	3	-	PROMETHEE	Yes	Municipal solid waste management
Moslehi and Arababadi [184]	2016	13	m	6	3	-	?	Yes	Electricity generation in the USA
Reuter [185,186]	2016	9	m	5	24	-	No	No	Li-Ion battery
AL-Nassar, et al. [187]	2016	8	m	3	2	-	Topsis	Yes	Wall–roof systems in Canada
Han and Zhu [188]	2017	3	e	1	1	-	Max	Yes	Recycling of discarded printed circuit boards
Nathanail, et al. [189]	2017	?	?	?	?	?	Yes	Yes	Urban fright traffic in Greek cities
Li, et al. [190]	2017	6	m	7	4	-	No	No	Solar PV technologies in the UK
Akber, et al. [191]	2017	11	m	5	4	-	Yes	Yes	Electricity generation in Pakistan:
Ahmad, et al. [192]	2017	11	m	7	6	-	No	No	Malaysian Food Manufacturing Sector ^{e}
De Luca, et al. [193]	2017	3	m	3	3	-	Min–max	Yes	Olive growing systems
Gürdür and Gradin [194]	2017	9	?	8	11	-	No	No	Automotive manufacturing ^{e}
Hannouf and Assefa [195,196]	2017	1	m	1	31	-	No	No	High-Density Polyethylene Production
Iacovidou, et al. [197]	2017	10	m	12	7	11	No	No	Anaerobic digestion of food waste ^{e}
Nguyen, et al. [198,199]	2017	5	e	4	- ^{j}	-	extern	No	Vegetable oil-based biodiesel
Wang, et al. [200]	2017	3	e	1	4	-	Benchmark	No	Fly ash concrete structures
Xu, et al. [201]	2017	3	m	1	3	-	Topsis	Yes	Ammonia production
Zajáros, et al. [202]	2017	7	m	1	?	-	Yes	Yes	DMSO solvent recovery
De Luca, et al. [193]	2018	3	m	3	3	-	Min–max	Yes	Olive growing systems
Aleisa and Al-Jarallah [203]	2018	6	m	1	6	-	Yes	Yes	Solid waste management in Kuwait
Aydin and Pinar [204]	2018	3	-	3	-	-	No	No	Electricity generation in Turkey (1995–2009)
Balasbaneh, et al. [205]	2018	5	m	2	3	-	No	No	Hybrid timber structure
Berriel, et al. [206]	2018	11	m	3	14	-	Benchmark	Yes	Low Carbon Cement in Cuba

Table 1. *Cont.*

References	Year	Analyzed Indicators					Normalization	Aggregation	Case Study
		Environment		Costing	Social	Tech			
		#	**m/e**	**#**	**#**	**#**			
Chen and Holden [207]	2018	1–12	m	1–4	1–12	-	Yes	Yes	Grazing dairy farm
Contreras-Lisperguer, et al. [208]	2018	19		4	12	-	No	No	Electricity cogeneration from sugarcane bagasse in Jamaica
Corona and San Miguel [209]	2018	4	m/e	7	3	-	Benchmark	No	Concentrated solar power
Ekener, et al. [210]	2018	14	e	1	?	-	Min–max cardinal ranking	Yes	Biomass and fossil transportation fuels
Gholipour, et al. [211]	2018	5	?	5	5	-	max	Yes	Petroleum refinery
Kamali, et al. [212]	2018	12	-	9	12	-	Benchmark	Yes	Residential modular buildings
Ma, et al. [213]	2018	8	e	1	1	-	No	No	Additively manufactured gear
Masilela [214]	2018	13	e	3	10	-	average	Yes	Biomethane vs. biohydrogen
Nathanail, et al. [215]	2018	10	-	36	52	42	max	Yes	Urban Freight Transportation
Opher, et al. [216]	2018	15	m	1	11	-	Yes	Yes	Urban water reuse
Pérez-López, et al. [217]	2018	10	m	2	8	-	No	No	Biotechnological carotenoid production
Reddy, et al. [218]	2018	10	m	6	22	-	Yes	Yes	Remediation alternatives for lakes
Mahbub, et al. [219]	2019	3	m	3	2	-	No	Yes	Oxymethylene ether
Abu-Rayash and Dincer [220]	2019	10	m	4	9	10	Benchmark	Yes	PV in Ontario

Tech.: technology; m/e: midpoint/endpoint; [a] to be chosen from 170 indicators; [b] Classification according to LCA concept; [c] based on 4 midpoint indicators; [d] based on 5 midpoint indicators; [e] discussed but not executed; [f] 10 indicators are proposed, only 1 is analyzed, [g] based on Stamford and Azapagic [71], [h] claims to follow Prosuite, [i] cultural indicators, [j] qualitative discussions, [k] based on Stamford and Azapagic [68], [l] socio-economic indicators.

2. Goal and Scope Definition

The goal and scope definition is the most important phase of an LCSA to shape the analysis. In particular, defining the system boundaries and the functional unit can be challenging when combining the three dimensions of LCSA. Furthermore, it is interesting to see what systems are analyzed.

2.1. Sustainability Approach

While sustainability is not a completely new concept, there is still not one universally accepted definition. Definitions often depend on the particular academic discipline. Almost half of the reviewed studies operationalize the idea of three elements of sustainability, namely environmental, economic and social as dimensions, pillars, or spheres. The notion of the "3 Ps": planet, people, and profit also goes along with this interpretation of sustainability. The main idea behind this three-dimensional concept is not to split up sustainability but to show that it is "a state where there exists a perfect balance between social, economic, and environmental processes" [181].

One of the key concepts of sustainability is Sustainable Development, which is defined as humankind's ability to develop in a way that present needs are met "without compromising the ability of future generations to meet their own needs" [221]. This definition, taken from the Brundtland report "Our Common Future" is referenced in a quarter of the reviewed studies. This is also the definition of sustainability given by the UNEP/SETAC guidance document for LCSA [8].

In Jørgensen, et al. [222] the authors take a closer look at the Brundtland definition in order to specify the goal of LCSA research. They filter out two key concepts that should be addressed in LCSA: Poverty, taken in relation to Sen [223] capabilities approach, and capital, defined to include natural, produced, human and social capital. Despite this differing conceptualization of LCSA Jørgensen, et al. [222] have concluded that LC methodologies are not able to capture the full breadth of sustainability. Consequently, they propose a different approach for LCSA than the one provided by [5]:

$$\text{LCSA} = \text{S-LCA}_{\text{modified}}, \text{ LCA and LC}_{\text{social capital}}$$

S-LCA$_{\text{modified}}$ refers to the inclusion of issues like poverty alleviation and produced capital in S-LCA whereas the idea of LC$_{\text{social capital}}$ is defined as "a yet unknown life cycle methodology" [222] to address social capital.

In a third of the reviewed studies, the authors do not provide a definition of sustainability conceptualization that they used for operationalization, while others refer to multiple concepts. Roughly 20% of the literature in this review develops a unique definition according to their respective LCSA case study or sector concerned. For example Moslehi and Arababadi [184] consider "sustainability as a [policy] design goal for decision makers". AL-Nassar, et al. [187] define sustainability as sustainable construction, which develops a built environment based on "resource efficiency and ecological design".

A seldom-discussed value-based question about the view on sustainability for LCSA has been presented by Schaubroeck and Rugani [224]. They postulate that LCSA has an anthropocentric view on sustainability (and not an egocentric, biocentric, or eccentric view). Their conclusion is that due to the anthropocentric view, LCSA should focus on human well-being, which not only consists of human health but also happiness. The other impact categories should always be assessed with regard to this purpose. As a practical consequence, they propose coupling LCSA with integrated earth system models. The same kind of model is also proposed by Schaubroeck [225]. In this publication, the author emphasizes the importance of coupling ecosystem service assessment with LCSA to assess human well-being.

2.2. System Boundaries

Traditionally the scope of an LCA is a process, service, product, which is defined by a certain process chain (product-orientated). In LCSA, this is also a system boundary which is frequently used for assessments. Together with broadening the scope of environmental indicators, also broadening the assessment object is sometimes postulated. Guinée, et al. [226] have defined a meso-level for assessments including technologies and an economy-wide scope for e.g., energy systems [226,227]. This might also include different tools for LCSA like input–output (IO) models [79]. In sustainability assessments outside LCSA, the assessments of regions and countries are also quite common. Quite recently Smetana, et al. [228] have also tried to use this system boundary for an LCSA by using IO models.

Despite this general discussion about system boundaries in LCSA, a more specific discussion between the different sustainability dimensions might occur. Preferably, all three dimensions should have the same system boundary. Nevertheless, particularly between LCA and LCC, differences arise [229]. A decision has to be made as to what extent it is appropriate to include early costs, such as R&D, leading to the inception of a product and cost, which arise after the development of a product, namely marketing costs [8,229]. Martínez-Blanco, et al. [96] have described in their article the differences between the system boundaries of the different sustainability dimensions in detail. They have shaped the boundaries for S-LCA based on the system boundaries for an LCA and LCC. Although in LCSA the system boundaries of the different assessment methods should be as similar as possible, the system boundaries for this S-LCA differ significantly. If the system boundaries had been identical, many processes would have been cut-off, and this would have had non-negligible effects on the overall results.

One approach to tackle spatial and temporal dynamic system boundaries has been discussed by Wu, et al. [41]. By using agent based modelling in the context of LCSA in a hypothetical example of green buildings, they are able to include behavioral dynamics from diverse stakeholders into the generation of the Life Cycle Inventory. Furthermore, the difference between the discounting LCC and the static LCA also leads to methodological discrepancies. Dynamic LCA approaches try to address this point [230,231] but they have not found much interest within LCSA yet.

2.3. *Case Studies*

The topics analyzed in the LCSA case studies (Figure 3) show a big variety of products, services, technologies and sectors. The main objects of assessments are energy related. Starting with specific products for electricity generation, e.g., PV modules [92], different types of electricity generation technologies are compared [164,171] and even future energy systems are analyzed [76]. Often, however, energy is also closely related to mobility because many mobility case studies deal with the production of fuel, e.g., [210].

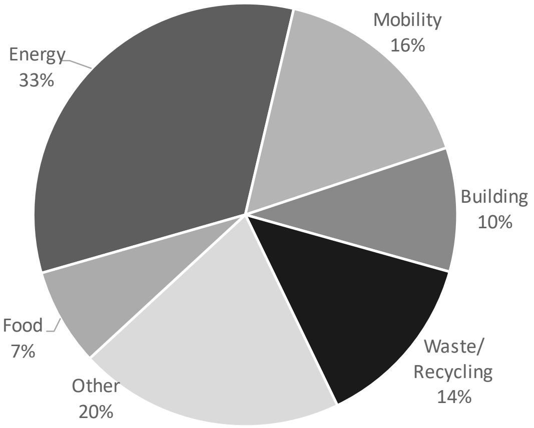

Figure 3. Analyzed topics in LCSA case studies and their relative shares.

3. Environmental, Economic, and Social Assessment within Life Cycle Sustainability Assessment

As most of the publications follow the three-dimensional approach, the three main methodologies in LCSA are now discussed in more detail. The discussion points are classified into aspects regarding the methods being used, the chosen indicators and limitations of the applied methodologies.

3.1. Life Cycle Assessment

LCA is the most mature and standardized methodology within LCSA. It was developed in the 1970s and has been standardized since 1997 [43,44]. Even though this methodology is less controversial than the S-LCA or LCC, harmonization does not completely restrict the procedure of LCA. This encourages practitioners to choose different approaches how to conduct the assessment.

3.1.1. Methods

As mentioned above, the method of LCA is standardized and all assessed LCSA papers follow this basic procedure. In the studies two main approaches are followed. Besides the widely used classical approach to assess a specific process chain of a product or service, LCAs based on economic input–output (IO) tables are also conducted. Rather than concentrating on details within the process chain the latter LCA approach concentrates on the supply chains of a technology or sector and wide resource requirements. This way less truncation errors are made [82]. This approach is mainly practiced by the research group at the Florida State University. Only two other publications are based on IO LCA [180,204]. In total 10% of all analyzed LCSA papers conduct IO-based LCA.

3.1.2. Indicators

There is quite a large variety among the analyzed LCSA studies regarding the chosen indicators, i.e., impact categories. Deciding between midpoint and endpoint impact categories is the most important choice to make. Life cycle impact assessment (LCIA) can approach the cause–effect chain of environmental impacts at two different points. Midpoint impact categories assess the environmental mechanism at some point between the interventions but before the actual damage. Endpoint impact categories actually look at the damage that is done at areas of protection that form the basis of decisions in policy and sustainable development. For the environmental domain, these areas of protection are human health, ecosystem quality and resource availability.

Eighteen percent of the analyzed LCSA studies apply endpoint impact categories. More than half of these studies additionally present results for midpoint impact categories to show the whole range of environmental impacts. As LCIA methods mainly Ecoindicator 99 and ReCiPe are used. The more recent ILCD method package was only used in three studies as well as IMPACT 2002+, also CML was used several times. Columbian Ecopoints [156] and assessment based on the NEEDS project [171] are rather unusual methods that have been used. Only one study failed to mention the LCIA impact method used [158].

The problem of nontransparent documentation of what is done within the LCA is higher on the midpoint level. Several studies, 6.5%, do not mention the applied LCIA method, e.g., [157,165,175]. For some studies, it can be deducted based on the calculated impact categories but for eleven studies not even that is possible. On the midpoint level, CML is most popular, followed by ReCiPe and the more recent ILCD method. Furthermore IMPACT 2002+ [183], TRACI [181], IWM-2 [172], and the Athena Impact Estimator [169,187] are used at least once. This reflects, on the one hand, the European focus of LCA studies (Asian authors also prefer the European methods) and, on the other hand, the fact that it takes several years for new LCIA method packages to be applied in publications. Several authors also add to the conventional extra indicators. These can be life cycle impact categories not included in conventional LCIA methods, e.g., cumulative energy demand [139,155] or the latest version of the assessment of climate change (IPCC 2013) [140] and not the one implemented in e.g., CML, but also additional indicators from other methods like material flow analysis, i.e., ratio of estimated cumulative primary material demand to geological availability [185]. In addition, case study specific indicators are quite popular, e.g., recyclability of the product [66], indoor air quality [72] or soil erosion [118]. Apart from the impact categories, one study [162] also gives values for single emissions, e.g., carbon monoxide. Some authors only account for the emissions produced by their product system but do not assess them in a proper impact assessment, e.g., [204,215].

An exception are the IO based LCA studies. The research group from the University of Florida does not use conventional LCIA methods but certain environmental footprints, e.g., water, carbon, or forestland footprint [79], while Choi, et al. [180] use the conventional impact category on climate change as well as special indicators, e.g., hazardous waste.

A totally new impact category is proposed by Scherer, et al. [232]. They assess animals' quality of life as well as the fraction of their original life span in different indicators. However, they do not see this as part of LCA but as a fourth dimension in LCSA.

One study by Corona and San Miguel [209] does not only conduct attributional LCA but also performs a consequential LCA to also assess changes in the target market.

3.1.3. Limitations

The limitations for LCA as a part of LCSA are mainly the same as for stand-alone LCAs. They comprise, inter alia, aspects regarding impact assessment methodologies, uncertainty analysis or allocation methods [233]. Within the studies analyzed in this paper, the biggest limitation is the nontransparent representation of methodological aspects, e.g., applied LCIA method, and the documentation of the inventory.

LCSA is about a comprehensive assessment of sustainability. Some studies, even though they assess indicators from all dimensions of sustainability, have a very narrow view on ecological sustainability. In those studies, e.g., [59,115], only one or two environmental impact categories are assessed, mainly climate change. This, however, is not the only important environmental impact that needs attention.

CML is a widely known and appreciated impact assessment methodology. However, this methodology has also been developed further and merged into the ReCiPe concept. Despite this, even new studies, e.g., [190,220], use CML. The same is true for Ecoindicator 99 at endpoint level, which has not been updated since 2000. Hence, more effort should be put into impact assessment method selection [234].

3.2. Social Life Cycle Assessment

The least mature part of LCSA is the S-LCA. In 2009 a UNEP/SETAC working group published guidelines to streamline the approach [235], which is currently under revision.

3.2.1. Methods

Methodologies for S-LCA are still actively debated and different concepts have been developed on the basis of the guidelines. One third of publications reference the UNEP/SETAC guidelines for Social Life Cycle Assessment [235] and the accompanying Methodological Sheets [236] as the most comprehensive and universally accepted methodological baseline. Roughly one fifth actually use the guidelines to build their methodological framework. The guidelines define five stakeholder groups (workers, local community, society, consumers, value chain actors) in which social and socio-economic impacts can be observed; however, most of the studies concentrate on the stakeholder group workers. Those studies that do not explicitly mention the UNEP/SETAC guidelines as basis for their S-LCA nevertheless follow a similar methodological procedure. They mostly refer to ISO 14044 as standard for LCA and transfer this approach to LCSA and its components.

The research group from the University of Florida uses an approach based on economic input–output data. In doing so, economic input–output data is multiplied with social and socio-economic indicator values to compare alternatives.

Another implementation for S-LCA with economic input–output tables is the Social Hotspot Database (SHDB) [237], which is applied in 9% of the studies to identify locations of particular social risks along a process chain, so-called hotspots. The SHDB is based on a global IO model derived from the Global Trade Analysis Project (www.gtap.org). The analysis by Valente [140] shows that the database approach is useful to identify hotspots along the supply chain, however the results only provide information on country-level and not on specific suppliers, which requires further analysis. Reuter [185] combines the SHDB results with case-specific economic data to create a "social risk profile sheet". This combination of hotspot analysis and site-specific data allows for a more detailed analysis of the particular product at the same time as the SHDB provides information on upstream processes. A similar database is PSILCA, which is using a more recent IO model compared to the first version of the SHDB. However, so far only two groups have worked with PSILCA [128,195]. Another important IO model used is the THEMIS model. "THEMIS is a hybrid input–output model, developed from the EXIOPOL database" [145]. The model is used in the PROSUITE project, which was initiated to develop a novel methodology for the sustainability assessment of innovative technologies. As can be said for all IO models THEMIS' purpose in S-LCA is to scale social impacts correctly to a specific sector and its associated workers since social data is mostly provided on a country or regional scale.

Approximately 30% of studies use interviews, either to develop a suitable indicator set for a specific case study, as part of data acquisition, for ranking in multi-criteria decision-making methods or to validate the quantitative analysis. Sims [72] uses a grounded theory approach to develop indicators for the sustainability assessment of heat-providing systems, which means that indicators develop from the case study instead of indicators selected from an existing theoretical framework. Such a qualitative approach has the advantage of being able to give a very detailed account of the circumstances in a particular case. However, it also involves a great amount of work and requires a large commitment from participating stakeholders, which might not always be possible to achieve.

3.2.2. Indicators

Even though the Methodological Sheets of the UNEP/SETAC Guidelines [236] provide possible indicators for each subcategory within the stakeholder groups, "a commonly accepted set of indicators has not yet been established by the scientific community and is still a controversial topic" [93].

One of the biggest challenges when selecting appropriate indicators to assess social impacts is scaling them to the functional unit because, compared to the environmental assessment, "one measures socioeconomic impacts, which are rather related to the behavior of a company instead of the function delivered by a given product" [238]. Even within a single company, occurrences, such as accidents, cannot always be allocated to a particular product or process. Indicators depicting the stakeholder's local community, society, consumer or value chain actors are even more generic in nature. In order to enable appropriate scaling, the S-LCA guidelines suggest using activity variables, such as number of working hours, to estimate the share of each unit process in the product system [239].

The publications presented in this review provide a wide range of indicators used for the social assessment of products and processes. For the selection of indicators, different approaches are used. Some studies explicitly refer to the UNEP/SETAC guidelines and the accompanying Methodological Sheets as a basis for selection. Others also mention stakeholder consultation and extensive literature review as possible methods. In addition, data availability is a key variable in terms of indicator selection (c.f. [93,96,184]). Another strategy to select appropriate indicators is the use of industry guidelines and political frameworks. Hu, et al. [129] refer to the Global Reporting Initiative (GRI) and guidelines of Corporate Social Responsibility (CSR) as basis for indicator selection. Santoyo-Castelazo and Azapagic [70] refer to global energy policy in order to identify the most pressing issues that should be assessed. Wulf, et al. [128] present a concept of how indicator selection can be guided by the UN Sustainable Development Goals. Some authors only provide a general idea of how indicator selection ought to be conducted but do not give a clear indication of how the indicators for their particular case were selected.

On average, seven indicators are used to assess social impacts. Out of the 146 studies, there are four studies that mention the necessity to conduct a social analysis; however, they do not include social indicators in their assessment. The minimum number of social indicators is one, whereas the maximum number is 23 in line with the Social Hotspot Database.

Most publications focus on the implications a product or processes have for the workers directly involved in the production process, while the stakeholder groups consumers and value chain actors are underrepresented [238]. Therefore, indicators related to health and safety statistics and employment implications are used most frequently. As a proxy to depict the health and safety level for workers the most frequently used indicators are non-fatal and fatal accidents/injuries in the workplace.

The creation of employment opportunities directly influences the well-being of workers and local communities by strengthening the local economic base directly and indirectly through the provision of supplementary services. Some of the indicators used to depict the employment implications are "provision of employment" [65], "creation of employment opportunities" [116], "Employment generation" [125], and "local employment" [135].

Choosing purely social indicators is often challenging. Consequently, some studies combine the social and the economic dimension and use socio-economic indicators for their analysis [79,80,83,89,150]. Others combine the social dimension with political implications [102,133,134], which is an attempt to include the dimension of public acceptance into S-LCA. Another possible combination used in a few of the studies is the socio-technical one, which takes into account aspects like human-machine interactions [69,133]. While some authors explicitly justify the combination of different aspects, others make the choice more implicit. Stamford and Azapagic [65], for example, use human toxicity potential and human health impact from radiation as indicators to depict human health, which indicates an overlap between S-LCA and LCA indicators. In general, such overlaps between S-LCA and LCA occur particularly in the realm of human health and resource use. In addition, the differentiation between S-LCA and LCC is not always clear-cut, particular on issues like contribution to economic development or employment generation.

3.2.3. Limitations

One of the main limitations is the selection of indicators measuring social impacts. As the framework for S-LCA is based on the general guidelines for LCA, the methodology predominantly favors quantitative data. While this is certainly not a limitation per se, in combination with limited data availability, it becomes difficult to adequately portray complex social interactions. While many researchers recognize this limitation and the importance of stakeholder involvement and comprehensive qualitative research to capture social complexities, cost-effectiveness, and time constraints often hinder their implementation [134]. Nevertheless, some authors use qualitative methods: Rettenmaier, et al. [118] conducted semi-structured interviews on working conditions in bio-refineries in France, Hungary, and Germany. Yu and Halog [122] conducted interviews with stakeholders along the PV process chain on qualitative issues like business ethics, influence of the solar industry on policymaking and transparency of business conduct. Others only mention the conduct of a qualitative social analysis but do not provide any further information [142]. Blok, et al. [145] use possibility of misuse, risk perception, stakeholder involvement, trust in risk information and long-term control functions as qualitative indicators in their analysis to compute a social well-being index. Whenever the computation of a single index for S-LCA is desired in order to allow for a combination with quantitative ecological and economic data, the qualitative data needs to be transformed into numbers. Therefore, some authors employ fuzzy set theory.

Fuzzy set theory provides a method to quantify linguistic terms [89] often obtained through expert elicitation, to determine the weights of criteria. Ren, et al. [101] use fuzzy set theory to quantify the social indicators. "Fuzzy set theory is a mathematical tool to address the imprecision and uncertainty that is inherent to human judgments [. . .] through the use of linguistic terms and degrees of membership" [101].

Especially in S-LCA, some indicators are very case-specific and difficult to transfer to other cases. For example, Buchert, et al. [30] use the weight of the product (bicycle) as a single social indicator in their LCSA. They argue that the weight of the bicycle affects the ergonomics for the worker and provides a higher power-to-speed efficiency for the costumer. While these arguments certainly hold true, it is debatable whether this indicator is sufficient to provide a comprehensive social assessment or contribute to the establishment of a universally applicable indicator set. The use of very case-specific indicators can also be explained by the lack of appropriate data. The guidelines therefore suggest combining site-specific data with generic data, for example on a country level.

3.3. Life Cycle Costing

LCC addresses the "economic dimension" of LCSA. Its scope can be direct, restricted to the economic competitiveness of a product or technology system, or can include wider economic impacts arising from the system [240]. Although LCC is the oldest form of evaluation there is no standard and several methods are established. UNEP/SETAC developed a Code of Practice, which defines LCC as " ... an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle ... ." [229].

To address the economic sustainability of a product or technology, its total costs are evaluated from the perspective of all actors directly involved with the product or technology [229]. This evaluation of total costs has different meanings for different actors involved along the life cycle. For instance, for manufacturers, it allows the comparison of a product's competitiveness with alternatives in addition to highlighting the key drivers of costs and areas in which improvements could be made. For government procurement, a major motivation for conducting life cycle costing was the recognition that there had been insufficient focus on the costs incurred during the operating life of a product or technology, whereas the investment or acquisition costs were viewed to be over-estimated [241]. Chang, et al. [94] have discussed the life cycle costs from the manufacturer's perspective and from the consumer perspective. The outcome of LCC, therefore, depends strongly on the actor's perspective.

3.3.1. Indicators

Indicators used in LCC refer both to the direct costs resulting from a product or technology and to the wider macro-economic impacts involved. Most commonly, studies calculate the components of life cycle costs and discount those to their present value, using a discount factor. Several studies feature investment analysis techniques, namely the internal rate of return, payback period, cost benefit analysis, return on equity and return on investment. Some studies use levelized cost of electricity as an indicator to express the life cycle cost of different electricity generation technologies. Other direct indicators used in the studies include value added from activities, profit and annualized costs. Macro-economic impacts are covered in one fifth of the studies and these correspond to more aggregate measures of the wider effect of the product or technology system on GDP growth, with certain studies discussing specific effects on elements, including: employment, tax, imports, exports, and R&D.

Investment parameters indicate whether investment in the product or technology is worthwhile, given the associated monetary benefits and costs. The net present value and internal rate of return are used to evaluate the financial return offered by a project based on an initial capital expenditure. Under the net present value method, future cash flows generated by the project are discounted to their present value, with the initial investment cost deducted from the sum of these discounted flows and this is done because financial returns in the future are considered less valuable than returns today [242]. In contrast, the internal rate of return (IRR) method evaluates the discount rate that would have to be applied to the project's future cash flows for the project to merely break even, with a higher IRR associated with a more financially attractive project [242]. IRR can be misleading—for instance, a project can have a higher rate of return (over one year) but add lower overall value than a project with a lower rate of return which delivers greater value over a longer period of time [242].

Under certain costing methodologies, there are norms regarding economic evaluation—according to the *Best Available Techniques* methodology, for instance, an investment is considered profitable if it has a payback period of less than three years [69]. However, this consideration depends on the technology, actor's perspectives and risk expectations. The payback period represents the time it takes for a project to generate sufficient returns to recover the value of an initial capital investment [242], so, under this rule, the returns from the project would have to equal the initial capital investment in less than three years. Likewise, Rettenmaier, et al. [118] consider an internal rate of return of 25% as the point at which an investment in new processing technology in relation to a bio-refinery concept is attractive. This rate of return relates to the specific branch of technology, in which they are active, namely new processing technologies and is based on estimations [243]. Other common indicators used in the studies to analyze direct economic performance include annualized costs [134,146] and total avoided costs, in terms of cost savings across areas like "raw materials, energy and labor" thanks to the adoption of a particular technology [69]. The annualized costs methodology entails the conversion of all investment costs into average annual flows, which can then be compared with the average annual benefit flows arising from the project [244].

Care must be taken when measuring indicators. It is important to ensure that reference values in which cost parameters are measured allow consistency and comparability among different product or technology systems. For example, reference values based on capacities may fail to take into account different levels of usage and, therefore, different operation and maintenance costs [164]. Certain cost parameters require special treatment. For instance, electricity costs will rise annually at a set rate and this is integrated into the calculation of the present value of annually occurring electricity costs [127,155]. Other matters, which may require special treatment in the analysis, include costs which are projected, thus subject to greater uncertainty, costs which are affected by state regulation, like subsidies, and distinctions between fixed and variable costs [56].

Whether a particular technology would lead to "additional economic growth that would not happen if one had invested in a different technology or sector" [145] is key to understanding the impact on prosperity, which results from the use of the technology [124,145,158,177,189]. Systems give rise to monetary flows consisting of components, such as imports, exports, profits, and wages, which contribute to changes in prosperity. Typical indicators of this nature, featuring in the studies, include: gross operating profit [83,86], total value added [114,115,129], wages [114,115,129], tax revenue [82], imports [83], and, ultimately, contribution to GDP [79,84,85,145]. Not all flows, emerging from the system, are positive, with imports considered to have an adverse effect on the economy, as increased imports result in a greater trade deficit and, thus, reduce GDP [83,145]. Technologies and products may have system level implications. Blok, et al. [145] refer to forward linkages involved in a product—its importance as an input to other sectors of the economy—as an indicator that the product enhances overall prosperity. Similarly, Kölsch [111] highlights the effect of a technology or product system on the number of firms in a market, with a larger number of firms implying a more efficient market, and on overall R&D, and, hence, economic competitiveness.

3.3.2. Methods

The use of economic input–output tables is typical of sources concerned with the wider economic impact of a technology or product system, with approximately 7% of studies using economic input–output models or hybrid economic input–output models to assess this impact. IO models, based on supply and use tables, illustrate the streams of money across different economic sectors arising from the technology or product system and can be at the scale of a region or at the scale of a country or even at a global scale [81,82].

A question arises as to whether externalities should be included in the LCC section. Whereas environmental economists generally require considerations of external costs, many LCA experts like Swarr, et al. [229] advise that externalities should only be included in the LCC section if they represent direct monetary flows or are likely to be internalized in the "decision-relevant future". Likewise, Weiss, et al. [138] argue, in relation to a case study based on aviation, against monetizing future environmental impacts, as these impacts feature in the LCA (environmental) section, measured in physical rather than financial units and they suggest that monetizing them in the LCC part could lead to "double counting". Around 7% of the sources included external costs specifically in the LCC section as opposed to in the LCA (environmental section).

According to Hunkeler, et al. [241] and Swarr, et al. [229], externalities—external costs that are likely to be internalized—should be converted into monetary values. Often, this conversion is straightforward, with Vinyes, et al. [154], for example, internalizing the cost of mitigating carbon dioxide emissions by converting the costs into monetary values via the international carbon dioxide market. Willingness to pay may offer a more realistic reflection of the actual meaning to society of environmental externalities, representing the "amount people are willing to pay not to lose the item in question", namely environmental well-being [245]. For instance, Menikpura, et al. [116] use the community's willingness to pay to avoid pollution-related health damage as a proxy for the environmental cost of the pollution emitted by the use of sustainable biomass in East Asia.

Tarne, et al. [246] have introduced the concept of a "product sustainability budget" which can be used alongside the LCSA evaluation as a decision support tool. Using the example of an automotive manufacturer selling various models of car, they suggest that certain customers may be willing to pay a premium for a car with a 'sustainability interior package'. This package, consisting of enhanced sustainability features, would be an optional add-on costing more than the standard and luxury interior packages. Customers could choose this more sustainable package, featuring a dashboard and cup holder made of more sustainable materials, over less sustainable versions, namely a dashboard made of plastic or one made of leather and exotic woods. Within the sustainability interior package, there is no reference made to wider sustainability metrics, like carbon dioxide emissions, or more detailed discussion of the environmental impact associated with the materials used in the sustainability package compared to the other packages. Part of the profits from this sustainability interior package would be reinvested in a product sustainability budget out of which sustainability improvements across the range of vehicles would be financed. Since these improvements are already accounted for in this budget, their additional cost does not adversely affect the overall LCC performance [246]. Crucially, this "product sustainability budget" acts as an interface with the LCSA evaluation, helping managers to identify sustainability improvements from the LCSA, which lead to the largest improvement in sustainability performance without negatively impacting the LCC performance.

3.3.3. Approach to Discounting

Discounting the future value of costs and benefit streams emerging from technology or product systems is very common in the LCC sections of the studies. Less than 20% of the studies explicitly mention the discount rate used to convert future values into present values. The most common discount rates are 10% and 5%. Other studies vary the discount rates used to simulate the impact of changes—for example, 0%, 5%, and 10%. More unusual rates include 12% [76], 7.6% [120], 4.17% [167], and between 3% and 6% [181].

The discount rate, which is set, depends on the particular decision maker and the goals of that decision maker [245]. Swarr, et al. [229] present guidelines as to which discount rate should be taken according to the actor from whose perspective the life cycle costs are being analyzed. For consumers, they recommend a rate related to the lending rate in their geographical area, whereas, for manufacturers, they suggest the internal rate of return typically used for investment decisions and, for government, the rate on bonds is appropriate. A common approach is to set the discount rate equal to the weighted average cost of capital (WACC) [127], thus reflecting different sources of capital for investment. If a system studied for LCC is less than two years, discounting should not be applied [136,229]. However, using a 10% discount rate as in many cases might also be relevant for a two-year project.

The discount rate used depends on assumptions about preferences in relation to future generations' well-being—the higher the discount rate, the lower the value placed on future generations' welfare, as monetary values (such as environmental and economic costs) in the future are more heavily discounted than under lower discount rates [245]. Inter-generational equity is a crucial ethical consideration in discounting, with this being especially complex in relation to technologies which have longer-term life cycles and it may be necessary to select a discount rate that offers a trade-off, reconciling economic efficiency between current and future generations [229]. Whilst Stamford and Azapagic [65] cite instances in which studies have used undiscounted costs for certain lifecycle stages to avoid neglecting the costs and benefits facing future generations, they warn that, not using a discount rate or using a very low discount rate is unrealistic from the perspective of financial investors. Discounting is an accepted and legitimate tool and, therefore, important in conveying the cost assessment [65].

An interesting matter is the discounting of future carbon dioxide costs. Rettenmaier, et al. [118] do not discount carbon dioxide avoidance costs. Discounting environmental costs increases the cost of carbon dioxide avoidance, as the same investment is made to avoid lower, discounted, future environmental costs. However, Rettenmaier, et al. [118] assume that environmental costs grow in line with the social preference rate, therefore, negating the effect of discounting. The assumption underlying this approach is that environmental costs increase over time.

3.3.4. Limitations

Two principal limitations in relation to LCC are mentioned here. The first concerns input–output (IO) models and the second concerns the treatment of externalities.

A limitation affecting IO models are "aggregation level uncertainties" [81], which can be caused when sub-sectors of the economy are assessed under a general, higher level main sector. This aggregation can lead to inaccuracies as to the impacts of the monetary flows arising from the technology or product system [81]. If sectors are not sufficiently reflected in IO models, it is often necessary to resort to process-level data, consisting of more detailed information relating to the inputs and outputs of that particular sub-sector [83,247]. An additional challenge with IO models is that they refer to a static point in time—in the case of Onat, et al. [82], they refer to the state of the different sectors involved in the production of alternative vehicles in 2002. However, the authors highlight that economic as well as social and environmental conditions evolve over time. This is a major problem, especially as IO accounts are not updated annually [82]. Further complexity can arise when working with different geographical regions—although attempts have been made at creating regional or global IO databases, such as the World Input–Output database, the level of detail often suffers and the data is frequently at a high level of aggregation, which makes comparisons more difficult [82]. Generally, it is possible to overcome these limitations by adapting sectoral IO structures (IO tables) and using dynamic IO models. However, methodologically this is very complex and needs a lot of data compilation.

Although many environmental economists are in favor of monetarizing externalities, the conversion of externalities into monetary values is controversial, since certain costs that arise in the future in connection with climate change are "difficult, if not impossible to estimate" [138]. Considering electricity as a consumer product, Nguyen, et al. [248] suggest that monetization of externalities is difficult, because there is little agreement about how to attach monetary values to the impacts arising from the production of power. However, they outline five possible tools which may allow the monetization of externalities in products. Three of these (EPS, ExternE, LIME) are based on calculating the population's willingness-to-pay to avoid damage to "safeguard subjects", namely categories contributing to human well-being and depending on the state of the natural environment. These correspond to "health", "biodiversity", and "ecosystem production capacity". Under the Eco-tax, the values attached to environmental impacts are based on the Swedish government's environmental taxes and charges, with a view that if the tax is fixed correctly, it should represent accurately the social value of action to mitigate environmental damage [248]. The impact assessment tool Stepwise 2006 simplifies the monetization of environmental impacts, focusing on three damage categories: (i) Human health, (ii) ecosystem quality, and (iii) resource productivity [248]. Simplified indicators convert each of these categories into monetary values. The value of health is measured by how much an individual can pay for one additional year of life, the value of ecosystems is assessed by how much of our well-being we are willing to give up to protect ecosystems whereas resource productivity is valued by the loss of future economic output caused by damage to the resource [248].

4. Normalization, Aggregation, and Weighting

The normalization, weighting and aggregation—together methods for multi-criteria decision-analysis (MCDA)—of different impact categories have already been actively discussed in LCA. In LCSA this topic is even more important as the complexity of results increases significantly. At the moment the variation goes from not normalizing, weighting and aggregating at all to full aggregation as well as something in between. Due to the early stage and the vast insecurities of LCSA as well as the different aims pursued, the UNEP/SETAC [8] advises the presentation of plain results without weighting and aggregation. In this way, a differentiated discussion of the problem without loss of information in the simplification process is possible. As discussed in Section 3.2. some social indicators do not provide quantitative results but instead a verbal discussion [118]. In that case only ranking methods [153] or fuzzy approaches [183] are feasible for aggregation. Furthermore, every user has to decide to what extent it is acceptable to allow trade-offs between the different indicators. In contrast, many other studies have applied weighting and aggregation [60,69,145,164]. On the one hand, the generation of results that are easier to communicate—not only for use in policy and economy but also for the scientific discussion—are preferred [249]. On the other hand, if weighting and aggregation are not explicitly performed, each reader implicitly attaches weighting to them according to their own value system, leading to different interpretations. How LCSA practitioners tackled these questions so far is discussed subsequently. For descriptions of different methods, please refer to external sources, e.g., [250–253].

4.1. Normalization

In general, there are two possible options for normalization. One is the use of internal statistical methods and the other is the valuation against external references. An alternative way is not to normalize but to rank the indicator results.

Internal normalization includes division either by the difference between minimum and maximum values (min–max) or by the individual minimum, maximum or a benchmark. When aggregating such normalized values, a full compensation between categories is possible, meaning that good results in one impact category compensate for bad results in other impact categories. The 'min–max' method attenuates these effects. Nevertheless, often a full compensation of results is not desired [251]. Another problem of internal normalization by division is that, after aggregation, the ranking order of the alternatives can reverse in rare cases, so called rank reversal. Due to this problem, internal normalization is highly controversial in LCA and most practitioners prefer external normalization [252,254].

As a second general method for normalization, external reference points can be applied. This can either be the relation to the global or local mean of this impact category per person or a political target value for this impact category [131,252]. By making use of these normalized results, the significance of the impact in a global context can be evaluated and the relevant impacts can be identified. This kind of normalization is more common in LCA separately. The application of external normalization factors, however, increases the uncertainty of the whole assessment, as the determination of these reference factors is complex and lack of data as well as inconsistent data can be sources of error. Furthermore, some impact categories describe local effects. A comparison with global values could cause over- or underestimated effects.

A further possibility to compare results is to rank them (*ranking*). The results for all analyzed options are ranked for each impact category [71]. This method also allows aggregation without full compensation between the impact categories. Furthermore, qualitative or semi- qualitative impact categories can be assessed.

The different LCSA case studies use a large variety of methods. One third of the studies neither normalize nor rank their results. They just display the results of the different indicators and discuss them qualitatively. On the other hand, 60% of the studies apply a normalization method and 4% use a ranking approach. In some studies, it is not clear what is done [121,125,202,203], but it is obvious that something is done. One study [126] discusses a ranking approach as well as normalization and Gencturk, et al. [181] normalize only the environmental indicators and leave the other indicators in their original state. In addition, several normalization approaches are applied in some studies. Akhtar, et al. [167] as well as Wulf, et al. [126] discuss different approaches while Grießhammer, et al. [56] first apply external normalization for the three dimensions of sustainability and normalize these three values by 'min–max'. The 'min–max' approach is the most common method for normalization, see Table 1, with 29% of normalizing studies. Another 13% apply external normalization. Most of the studies normalize against a global or local mean value per person, e.g., [56,145]. Only two studies from the same working group choose a political target as an external reference [131,132]. Under the studies that use other methods the approaches to normalize against the maximum, minimum or benchmark value are subsumed. Furthermore logarithmic normalization [218] or the special concept TOPSIS, i.e., vector normalization [80,86,182,187] as well as PROMETHEE [102,183], an outranking approach, fall into this category. Another 15% of the studies do not state what methodology they use.

4.2. *Aggregation*

Different methods of aggregation can be applied to bring the different impact categories of an LCSA together. Most common are linear aggregation methods in which full compensation between the different impact categories is possible depending on the normalization method.

Another possibility is geometrical aggregation, which does not fully compensate for the impact categories even when normalizing the results by minimum or maximum. By using this method, low normalized impact category results have a bigger influence on the final score.

Of the analyzed case studies, 56% decided to aggregate their individual indicators to one result. Some studies aggregate only parts of their results, e.g., within one sustainability dimension [181,184,207]. Those numbers show that not all studies aggregate their normalized or ranked single results [118–120,199]. For example, studies that display their results in a spider or radar chart normalize their values without aggregating them [82,83,122]. At the same time, it is also possible to calculate the area of a spider chart as an aggregation approach [69,131,132]. These results, however, can be biased by the layout of the indicators within the chart [255]. Geometrical aggregation is very uncommon. Only three studies mention it [126,162,220]. Also more complex methods for aggregation, e.g., outranking methods, are rarely discussed [256]. TOPSIS [105,182], PROMETHEE [102,183,219], as well as VIKOR [101] are the only ones applied in case studies. Simpler outranking approaches are applied in six studies [70,71,145,148,153]. Vinyes, et al. [154] also integrate indifference threshold values in their outranking methodology.

A quite complex approach is followed by Kouloumpis and Azapagic [78]. After normalizing, the LCSA values are aggregated within each sustainability dimension. However, they are not simply aggregated but fuzzified, aggregated with the help of if-then rules and defuzzyfied. The same process is repeated to aggregate the three dimensions to one sustainability score. The goal is to "overcome issues [. . .] with imprecise or uncertain information related to indicators and other inputs. Moreover, it can deal with a differing number of indicators within the three sustainability aspects without affecting the overall results" [78].

4.3. *Weighting*

For the identification of weighting factors, several methods can be used. First, using equal weights for all impact categories or for each dimension of sustainability is the simplest and most common way [251]. Together with a sensitivity analysis, this method can deliver robust and reliable results [69,252]. As an alternative, stakeholder or experts can develop a weighting set in a workshop or a survey for a particular study. To support or guide this procedure, mathematical methods like analytic hierarchy process can be used. From political targets, also weighting factors can be calculated, for example, with a distance-to-target approach [257].

If results are aggregated in a study, they also have to be weighted. Due to several reasons (e.g., restricted resources, robustness of the results), many studies perform some kind of equal weighting. This means that all indicators have the same weight regardless of the different dimensions of sustainability, or that the different dimensions of sustainability (economy, environment, social well-being) have the same weight while single indicators have different weighting factors, or that the different dimensions of sustainability have the same weight as each indicator within one dimension (Some studies discuss several approaches, which is why added numbers can be different from the initial percentage). For some studies, one of the major themes in the discussion is the variation of weighting factors and its influence on the results [59,81,84,126,127,210,220]. A recent development in this field is the introduction of different stakeholder profiles (Egalitarian, Hierarchist, and Individualist) based on cultural theory [210,220]. Other studies have conducted surveys or workshops with experts and stakeholders to determine weighting factors. This approach has also been chosen by Tarne, et al. [258]. For the three different sustainability dimensions, they have determined an almost equal importance (economy 33.5%, environment 35.2%, and social issues 31.2%). In three studies, the authors themselves defined the weighting factors. Studies that have equal weights for the sustainability dimensions but different weighting factors for the single indicators derived the weighting factors either from surveys among the general public (SEEbalance studies e.g., [111]) or relied on their own judgment [167]. The most common method to derive unequal weighting factors is the analytic hierarchy process (pairwise comparison of indicator importance). Other methods used are Intuitionistic Fuzzy Multi Criteria Decision Making [80,86] and direct rating [145].

Although weighting is a very important part of LCSA and might influence the results significantly, only few studies conduct a sensitivity analysis regarding the weighting factors.

4.4. Limitations

MCDA is a value-based process that the authors need to handle with elaborateness. Depending on whom the addressee of the LCSA study is it can be appropriate to display and discuss just the results of the single indicators. A fellow scientist probably wants most of the information without predefined values. Decision makers in economy and politics, on the other hand, might prefer aggregated results if the value system behind the aggregation is clear. The case studies analyzed here mostly do not mention their target group except SEEbalance and PROSA, which are methods developed in or for industry. As most of the case studies, however, are published in scientific journals most of the readers will be scientists. Irrespective of the addressees, it is most important to describe everything in a way that is transparent and reproducible. Although this should be standard and not worth mentioning not every study analyzed here fulfills that prerequisite.

Most of the studies agree that, if aggregation is favored, a full compensation between the indicators should not be allowed. When also integrating qualitative results outranking methods are probably the way to go. Also more elaborate approaches that include preference and indifference thresholds might improve this part of LCSA [126,252].

5. Important Influences

5.1. Special Concepts for LCSA

As the previous three sections have shown, the individual methodologies of LCSA permit a considerable variety regarding its usage, considering not only the three Life Cycle methodologies, but also additional methodologies that can be integrated in an LCSA. Over recent years, different scientific groups developed special concepts to streamline LCSA and to improve its manageability, which are presented in detail in the following section. Furthermore, life cycle based approaches for raw materials and resource efficiency in particular have been presented [259–263].

5.1.1. Product Sustainability Assessment PROSA

One of the oldest concepts is PROSA [56] by Öko-Institut e. V. It originated from a publicly funded project in Germany and is based on earlier works by the institute [55]. It concentrates on products, product portfolios and services. However, assessments of technologies, large infrastructural projects or geographical units are also possible. The main goals of this methodology are "strategic planning and product portfolio analysis in companies, product policy and dialogue processes, sustainable consumption and product evaluation as well as product development and marketing" aiming for application directly in companies [56]. Therefore, in addition to the common LCSA tools LCA, LCC, and S-LCA product portfolio analysis, risk assessment, eco-efficiency analysis, benefit analysis including consumer research, and MCDA are also part of this approach. The indicators for the sustainability assessment itself are predefined. Special attention is thereby given to the S-LCA. A long list of 170 indicators to choose from is proposed clustered into the stakeholder groups employees, local and regional community, society and users and consumers. These groups are further subdivided in e.g., social security or job satisfaction. An indicator itself might be "Duration and level of wage continuation in the case of illness" within social security. This LCSA approach has been used for product declaration ("blue angel") [264].

5.1.2. New Energy Externalities Development for Sustainability (NEEDS)

New Energy Externalities Development for Sustainability (NEEDS) was a project under the 6th Framework Programme of the EU, lasting from 2004 until 2009. 80 different partners from 30 countries representing universities, research institutions, industry and NGOs were involved. According to the project "Its ultimate objective is to evaluate the full costs and benefits (i.e., direct + external) of energy policies and of future energy systems, both for individual countries and for the enlarged EU as a whole" [265]. Besides the LCA of energy technologies and the monetary valuation of these technologies, also the integration of these two aspects into policy formulation and scenario building were goals of the project. The project focused on quantifying technologies, e.g., development of a Life Cycle Inventory database (http://www.needs-project.org/needswebdb/index.php). However, by performing a life cycle based sustainability assessment with MCDA as well as a total cost approach several methodological issues regarding LCSA were tackled. Bachmann [266] pointed out several topics from the analysis, e.g., the strict use of three dimensions is often hard to follow because indicators can be integrated in more than one dimension. Finally, he argued that LCSA should make a clear cut distinction between the sustainability dimensions either on the inventory level or at the endpoint level. Furthermore, he fosters the introduction of risk into LCSA, the assessment of social and/or environmental benefits and the development of weighting factors based on globally harmonized principles, e.g., by the UNEP/SETAC [266].

5.1.3. Co-Ordination Action for Innovation in Life Cycle Analysis for Sustainability (CALCAS)

This project ran also under the 6th Framework Programme of the EU and consisted of scientists from The Netherlands, Sweden, Germany, France, Portugal, United Kingdom and Italy [267]. They call their kind of life cycle based sustainability assessment "Life Cycle Sustainability Analysis". While the LCS Assessment conducts three separate assessments based on the same life cycle approach LCS Analysis proposes a joint modelling phase for the three sustainability dimensions to include all synergies, linkages, and side effects between those three [227,268,269]. Furthermore, LCS Analysis should be "broader and deeper" than a conventional LCA. Broader in a sense of not only including economic and social indicators besides environmental ones but also broadening the object of analysis from process chains to technologies to industrial sectors [226]. Instead of conducting three separate analyses, a single one should be done holistically. Furthermore, the conventional LCA phases "inventory analysis" and "impact assessment" are merged to one modelling phase. From a product-oriented point of view, this can lead to baskets of commodities and sectors and even economy-wide analyses [270]. Broadening might also include integrating the different indicator results by weighing and aggregating [271]. Deepening the assessment comprises several possibilities. This might be consequential LCA, input–output models including hybrid LCA and spatial differentiated models. In addition, normative aspects can be introduced to the analysis, e.g., weak versus strong sustainability, weighting or discounting [226,270]. A certain set of indicators or models to use, however, are not defined. Even though, Sala, et al. [47] preferred this approach to the approach by Klöpffer [5], it has not proven its operationalization yet. The most recent papers connected to this approach discussed certain methodological topics, i.e., combining LCA and LCC [272], system description [273] and goal and scope definition by defining a technology map [130]. Recently attempts have been made to develop this approach further to a Life Cycle Sustainability Unified Analysis (LiCSUA) that also includes stakeholder engagement, rebound effects, vulnerabilities, and resilience, as well as data uncertainty and risk aversion [274]. Providing also an operationalization of this approach, parts of it were tested using a hypothetical case study. However, further real case studies need to be conducted to prove the feasibility of the total approach.

5.1.4. Prospective Sustainability Assessment of Technologies (Prosuite)

Prosuite was also developed for the EU under the 7th Framework Programme and consisted of scientists from The Netherlands, Norway, Denmark, Belgium, Germany, Austria, Spain, Switzerland, France, Hungary and Portugal as well as industrial partners [275]. The aim of this project was to develop an assessment method for (new) technologies on which decision-makers can act on. A focus is on the applicability of this approach, which is underlined by the provision of free software. This approach disengages itself from the conventional three-dimension model of sustainability. Instead, five impact categories are proposed that cover "Human Health", "Social Well-being", "Natural Environment", "Exhaustible Resources" and "Prosperity". For those dimensions as well as the underlying indicators, e.g., 'Regional income inequalities', weighting factors have been determined in workshops by technology experts for the MCDA. Prosuite, furthermore, is one of the few approaches that use endpoint indicators, see Section 5, for their evaluation. As a consequence, for example, climate change influences the impact category "Human Health" as well as twice in "Natural Environment" by contributing to terrestrial and freshwater ecosystems. For some indicators in the impact categories "Human Health", "Social Well-being", and "Prosperity" the economic IO model THEMIS is used. Within this project four case studies were executed [145]. However, no new applications have been documented, yet.

5.1.5. Integrated Life Cycle Sustainability Assessment (ILCSA)

Another approach is pursued by ifeu (Institut für Energie- und Umweltforschung Heidelberg). For their accompanying research of the 7th Framework Programme projects, e.g., BIOCORE or SUPRABIO [118,119], ifeu researchers developed their own methodology called Integrated Life Cycle Sustainability Assessment (ILCSA). Based on the LCA, LCC and S-LCA they are integrating other topics, e.g., local environmental effects. Additionally, a barrier analysis is part of the methodology, which tackles feasibility, stability and implementation potentials and competition aspects. This might include feedstock availability (this methodology is concentrating on biorefineries and other biomass based process chains), legal aspects or risks. This is especially important because like Prosuite also ILCSA has the aim to assess new technologies, processes or products. These assessments are conducted for different process configurations (scenarios), which are compared in a benchmark analysis against each other and/or an external scenario. Here not only quantitative but also qualitative indicators can be included because only a simple rating with colors or +/− is conducted. Even though no result integration by aggregation and weighting is conducted, this simple color code is supposed to facilitate decision making. Several case studies have been executed by ifeu but no other researcher has adopted this methodology yet. [118,120]

5.1.6. Tier Approach

The so-called Tier approach, first presented by Neugebauer, et al. [276], goes into a different direction. In this approach three different tiers are defined, which include different levels of comprehensiveness of LCSA regarding the indicator selection. The first tier is called "sustainability footprint" and includes only one indicator for each sustainability dimension, i.e., global climate change, fair wage and value added. With its indicators, this tier focuses with its indicators on globally relevant and practical indicators so that it is easy to apply. In the second tier, the indicator set is expanded to six environmental, four social and three economic indicators. This represents a "best practice" indicator set with robust indicators for the complete supply chain. For the third tier several additional indicators are included (in total ten environmental, seven social and six economic indicators). This "comprehensive assessment" includes also new topics of LCSA, e.g., cultural heritage. It is not even clear yet how to apply these indicators. It requires a skilled practitioner in the field of LCSA to handle these different levels of maturity. In general, this approach tries to find a low entrance level into LCSA and gets more advanced if needed. As different numbers of impact categories are considered and different modelling principles are followed, the authors recommend a separate discussion of the different indicators and no aggregation scheme. Up to now only one practitioner [207] outside this research group has applied this approach [99,277].

5.1.7. SEEbalance

Many industrial companies have their internal sustainability assessment tool, but do not release it publicly. BASF, in contrast, published methods and results of their SocioEcoEfficency Analysis (SEEbalance) scientifically [60] with the help of research organizations (Institute for Geography and Geoecology of Karlsruhe University, Öko-Institut e. V., and the University of Jena). The goal is to directly compare product and process alternatives based on all three sustainability dimensions. The core of this approach was in the beginning the social profile, which included five different stakeholder groups, e.g., future generations. One indicator in this group would be, for example, number of apprentices [113]. This has recently been changed to a Social Life Cycle Assessment accompanied by a Social Hot Spot Assessment to keep up with current developments in science and industry [278]. These assessments are accompanied by an ecological efficiency assessment. The weighting factors for the calculation of aggregated values are based on surveys among the population.

5.1.8. Limitations

All approaches presented lack a broad dissemination because no other research groups apply them. Some approaches are not designed to be used by others, e.g., PROSA is used as a label for products and no scientific publications regarding the methodology are published. SEEbalance does publish some scientific papers, but does not reveal every aspect of the methodology, e.g., weighing factors. Likewise, the scientist behind ILCSA do not promote their approach directly but rather used it as their assessment methodology for biomass related product systems, even though this approach might also be helpful for the assessment in other projects. Similarly, NEEDS is a framework that should not be used in other case studies, but helped significantly in the discussion process of LCSA. The other three approaches, however, claim to be general. CALCAS provides many interesting ideas and shows how an LCSA should be done ideally, but it is quite complex and vague at the same time. It lacks operability. Prosuite, in contrast, gives a clear structure for LCSA. In a more industry driven context, this might be welcome. For scientific purposes, these constraints might be too strong. Using endpoint impact categories for the LCA while most of the LCSA studies prefer midpoint impact categories is one example. However, this work can be helpful regarding indicator selection. Furthermore, the classification into five fields of sustainability instead of the standard approach with three dimensions helps thinking outside the box even though others might not share their conclusions. The tier approach is the newest development in this field. It gives no full framework on how to conduct LCSA but it might help with indicator selection in general. Other questions, e.g., regarding aggregation, still need to be addressed by the evaluators.

5.2. Current Developments

The EU fostered Life Cycle Sustainability Assessment also in the more recent Horizon 2020 projects "Sustainable Process Industry through Resource and Energy Efficiency—SPIRE" [279]. This program has the aim to identify "Methodologies, tools and indicators for cross-sectorial sustainability assessment of energy and resource efficient solutions in the process industry". SPIRE was a public private partnership with the vision " … to reduce resource and energy inefficiency and the environmental impact of industrial activities" [280].

The project "Sustainability Toolkit for easy Life-cycle Evaluation—STYLE" (2015–2016) aimed at developing an ideal toolkit framework for sustainability assessment of technologies, with a Technology Readiness Level (TRL) between four and seven. A comprehensive quantitative sustainability assessment beyond TRL seven was out of the scope of this project. A three-stage framework has been developed beginning with a "Materiality Setup" to identify the important system parameters, corporate priorities, objectives, and expectations. The second stage contains an "Integrated Qualitative Screening Tool", which is based on qualitative questions to score the technological solution. The third "Semi-quantitative Assessment Toolset" stage consists of an economic, an environmental and a social module. It is supposed to be a semi-quantitative screening tool [281].

From 2015 to 2016 the project "Sustainability assessment methods and tools to support decision-making in the process industries—SAMT" reviewed and clustered methods for evaluating sustainability in the process industry. This project included—unlike STYLE—also comprehensive sustainability assessment methods. A comprehensive overview of sustainability assessment methods and tools also from the industry is given by Saurat, et al. [282] and Saurat, et al. [63]. As further results of the project, a vision, a roadmap and an implementation strategy for sustainability assessment have been developed [283]. The roadmap identifies drivers, bottlenecks and industrial needs for the development of sustainability assessment. Furthermore, it sketches solutions for the fields methods, tools, data and co-operations.

The project "Metrics for Sustainability Assessment in European Process Industries—MEASURE" analyzed the current state of life cycle based sustainability assessment and has also developed a roadmap regarding this topic [284]. The authors demand to enable and promote life cycle based tools for sustainability assessment, harmonization of databases, methodological choices and communication of results in industry and research as well as the support of data exchange and cross-sectional collaborations. These demands are supported by teaching and background documents regarding, for example, the current state of LCSA [48] or multi-criteria decision-analysis [250].

For the development of LCSA, the projects SAMT and MEASURE provided helpful input by integrating an industrial perspective into the discussion. Furthermore, they developed good overview material for further discussions.

6. Conclusions

This paper gave an overview of the development of LCSA and the recent accomplishments and challenges in this field. Two-hundred and fifty-eight publications have been identified as LCSA publications from 1997 until 2018. In particular, in 2012, following the publication of the UNEP/SETAC document [8], a significant increase in publications can be observed and this is repeated again in 2017 and 2018. Since 2017, it is also obvious that the LCSA community has diversified. Before that, several groups published a significant share of the articles in the field, e.g., from the University of Central Florida or the University of Manchester, representing different schools of sustainability assessment. Despite this broadening of LCSA publications, a certain stagnation can be observed. Discussions have a very specific focus, e.g., on dealing with uncertainties in MCDA [103,106,108] or finding weighting factors by the analytical hierarchy process for a specific case study [215,216]. More general questions regarding, for example, different actor perspectives and what this means for the different methods, are no longer at the center of the discussion despite not yet having been solved. Furthermore, many papers applied a pragmatic approach, because existing frameworks are either too narrow and do not give scientists enough freedom to conduct their assessment as they see fit, e.g., Prosuite, or are too broad to give guidance as to how to perform an LCSA, for example CALCAS. The suggested contributions of this review are both a greater methodological development of LCSA and better guidance as to the implementation of LCSA.

From the 258 publications, 146 discuss a case study at least to some extent to operationalize LCSA. In one third of these studies, energy related technologies are assessed and another 16% deal with mobility aspects. These are the most important fields of technology when discussing reductions of greenhouse gas emissions. It therefore appears that burden shifting from climate change impacts to other harmful environmental impacts is at least discussed and the need to include economic and social implications is recognized as well.

After many years of LC(S)A, frequent demands for greater transparency as well as thorough goal and scope definition have been made, but there is still plenty of room for improvement. In particular, methodological choices, e.g., about impact assessment or normalization methods, and inventory data should be well documented and justified. Surprisingly, many publications lack a transparent description/discussion about their understanding of sustainability. Many publications implicitly use the three-dimensional concept because it is the logical prelude to Klöpffer's LCSA approach [4,5] (Section 2.1.). For implementation, however, this leads to difficulties in the classification of the different indicators because often an indicator can be classified in different sustainability dimensions [266,285]. This leads to later problems during the additional multi-criteria decision-analysis (MCDA) stage. However, it also helps to address more accurately the meaning of each dimension of sustainability. It would also be helpful to define, in a more specific way, the understanding of sustainability, which is adopted with regard to MCDA (Section 4.). This means that the theoretical implications behind choosing an MCDA method need to be addressed thoroughly. Similarly, the connection between the Sustainable Development Goals (SDGs), indicator selection and LCSA is still under discussion [128,286].

The combination of the three different life cycle methods also brings the specific problems from each assessment, i.e., LCA, LCC, S-LCA, to LCSA. This includes, for example, the definition of different actors for LCC or the high uncertainties of the impact category human toxicity in LCA. However, the biggest challenges still lie within S-LCA regarding the selection of indicators, impact assessment, handling of (semi)qualitative results etc. Hopefully, the introduction of the revised S-LCA guidelines [287] will help to consolidate S-LCA. In the worst case, LCSA will only experience limited development until S-LCA is mature enough to keep up with the other methods in LCSA. Furthermore, there are difficulties that more or less all methods within LCSA have to face, in particular data availability.

After the realization of different EU projects to operationalize LCSA, which came up with some helpful suggestions which were, however, not implemented in practice, the question arises if there will be another international attempt, e.g., by UNEP/SETAC initiative or EU calls, to advance LCSA.

The goal for the future development of LCSA must be that the framework is specific enough to give some guidelines for the execution of an LCSA without being too narrow to obstruct the development of scientific questions. Regarding the different purposes and audiences for LCSA, it must be possible to keep it quite simple, respecting some minimal standards regarding transparency and thoroughness or to do it in a more complex way. This leads to the last challenge of LCSA regarding the communication of results from LCSA. Such an assessment can lead to a plethora of results and the presentation of results must achieve a balance between simplicity and transparency for the sake of the audience.

The positive momentum to address a complex system within its technical and economic boundaries and at the same time keeping the social implications in mind should help to sort out the various (methodological) challenges still existing in technology assessment. The increasing number of studies as well as the variety of practitioners support this approach.

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