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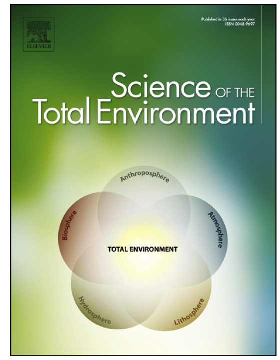

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A systematic review of life cycle sustainability assessment: current state, methodological challenges, and implementation issues

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Abstract

The life cycle sustainability assessment (LCSA) is a tool to assess sustainability from a life cycle perspective, which has been receiving increased attention over the years. This work presents a systematic review of the current application of LCSA, presenting the foundations, main methods, current operationalization state, and major challenges to its broad implementation. The review protocol considered the search of keywords in Scopus and Web of Science databases. The search has considered the literature published or in the press until December 2018, resulting in the selection of 144 articles written in English. Of those, 71 articles operationalize LCSA in real case studies, while the remaining consist of review, viewpoint, and methodological development articles. This review demonstrates that the use of LCSA has been increasing in recent years. Today, the most applied approach is to consider LCSA as the sum of life cycle assessment, life cycle costing, and social life cycle assessment because it is built on the methodologies that already exist and are under continuous development. However, the lack of harmonization of the methodology is a central challenge to its operationalization. Therefore, LCSA still requires further improvement in, among others, definition of coherent system boundaries, the development of robust databases to allow the assessment of economic and social perspectives, definition of impact categories that allow comparability between studies, development of impact assessment methods, development of methods to carry out uncertainty analysis, and communication strategies. Besides, further case studies should be developed to support the improvement of the methodology and a better understanding of the interaction of the environmental, economic, and social aspects.

Keywords: Life Cycle Sustainability Assessment (LCSA); Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Social Life Cycle Assessment (SLCA); systematic review

1. Introduction

Nowadays, there is an increasing need to assess the sustainability of products, systems, and technologies, and several tools have been developed for this purpose (Finkbeiner et al., 2010). Among these tools, life cycle assessment (LCA)[1] is widely used for decision-making and supporting policies. Even though the scope of LCA is limited to environmental impacts, the first conceptual idea of integrating the economic and social pillars of sustainability into LCA can be traced back to 1987 (Finkbeiner et al., 2010; Oeko-Institut, 1987), followed by the works of O'Brien et al. (1996), who discussed the integration of both social and environmental impacts, and Norris (2001), who suggested the integration of life cycle costing (LCC) analysis.

The integration of the three pillars of sustainability from a life cycle perspective is referred to as life cycle sustainability assessment (LCSA). This terminology was used for the first time in the work of Zhou et al. (2007) and was then further developed in other studies (Cinelli et al., 2013; Kloepffer, 2008). LCSA gives the highest level of assessment among the existing environmental and sustainability tools (Finkbeiner et al., 2010) once it encompasses environmental, economic, and social aspects, i.e., the pillars of sustainability, allowing a more holistic understanding of the sustainability of products and processes, which translates into better support for decision-makers (UNEP/SETAC, 2011).

There has been a growing interest in LCSA methodology in recent years, but several issues remain unclear, such as how to apply and how to address its emerging methodological challenges (Guinée, 2016; Zamagni, 2012). In the same way, LCA has undergone a phase of conception when diverging approaches coexisted on its earlier years (Guinée et al., 2011); the LCSA is currently experiencing a similar phase toward the construction of a more robust methodology. Even though LCSA is built upon the scope of ISO 14040:2006 (ISO, 2006a), a standardized procedure on how to conduct LCSA is still lacking, and thus, LCSA studies are being carried out by applying different methods. These constraints make difficult the use of LCSA by practitioners and the comparison of LCSA results.

Therefore, the objective of this paper is to carry out a systematic review of articles on LCSA published in peer-reviewed journals, to identify the type of studies that have been developed to date, and how practitioners are applying LCSA. A systematic review aims to systematically search, appraise, synthesize, and summarize research evidence (Grant and Booth, 2009). This work is structured as follows: besides this introduction, Section 2 presents a brief background on LCSA concepts and methodology, Section 3 describes the methodology adopted in this systematic review, Section 4 presents the results, Section 5 provides a discussion of the main challenges identified in the review, and finally, Section 6 includes the final remarks of the review.

2. Background

The terminology of LCSA was first adopted in the study of Zhou et al. (2007), but the first conceptual ideas can be identified in 1987 in the methodology “Product Line Analysis” developed by the Oeko-Institut in Germany (Finkbeiner et al., 2010; Oeko-Institut, 1987). The integration of social and economic aspects into LCA has been discussed in the scientific literature since the 2000s (Hunkeler, 2006; Klöpffer, 2003, 2006; Rebitzer and Hunkeler, 2003;

[1] In this study, the acronym LCA stands for the environmental Life Cycle Assessment.

Weidema, 2006), and the first conceptual scheme for LCSA was proposed by Kloepffer (2008). It consisted of two approaches, namely:

- LCSA as the sum of an environmental LCA, LCC, and a social life cycle assessment (SLCA) without any formal weighting between them, which is presented by LCSA = LCA + LCC + SLCA; and
- (2) LCSA as a new assessment built on the same inventory, i.e., LCSA = new. This implies, including LCC and SLCA, additional impact categories in life cycle impact assessment (LCIA).

Some disadvantages have been pointed out to the use of the first approach because it is time-consuming, as it requires specifying a life cycle for each one of the methodologies, and it may lead to inconsistencies related to the possibility of establishing different boundaries and different allocation rules (Heijungs, 2010; Heijungs et al., 2010; Kloepffer, 2008). To overcome these issues, the Coordination Action for innovation in Life Cycle Analysis for Sustainability (CALCAS) project, funded by the European Commission, has proposed another conceptual framework for LCSA (where the "A" no longer refers to "assessment," but to "analysis"). This framework consists of an integrated approach that incorporates environmental, economic, and social aspects into the same technological system (Zamagni et al., 2009).

As the interest in LCSA has been increasing, different approaches for LCSA application have been proposed. In the "Workshop on life cycle sustainability assessment: The state of the art and research needs" held in 2012 in Denmark and systematized in Cinelli et al. (2013), Walter Klöpffer proposed two additional approaches to standardize LCSA, besides the ones already mentioned (LCSA = LCA + LCC + SLCA; LCSA = new):

- LCSA as the sum of the eco-efficiency and an SLCA, which may consider the application of the International eco-efficiency standard ISO 14045:2012 (ISO, 2012).
- LCSA as the sum of LCA and socioeconomic analysis, as proposed by the Institute for Energy and Environmental Research (IFEU) in Germany.

Part of the challenge toward the implementation of LCSA is related to the difficulties in the use of SLCA and LCC from a life cycle thinking perspective. The SLCA methodology has attracted great interest in recent years, and scientific research has increased toward the development of robust methods (Petti et al., 2018; Wu et al., 2014). However, important challenges in its operationalization remain, such as the quantification of social data and its correlation to the functional unit, the availability of data, the choice of indicators, and the selection of comprehensive methods (Guinée, 2016; Kloepffer, 2008; Zamagni et al., 2013). Regarding the LCC, it was proposed as a life cycle-based method for the economic pillar of sustainability in the earlier 2000s (Klöpffer, 2003).To date, there is no standardized procedure to conduct LCC, but a code of practice based on the ISO 14040:2006 standard has been proposed (Swarr et al., 2011). Some of the challenges regarding the use of LCC are the availability of data, the use of different currencies, the definition of discount rates, and the relevance of life cycle costs for the different stakeholders (such as customers, companies, or society in general) (Swarr et al., 2011).

3. Materials and methods

The present study provides a systematic review of the current state of development of LCSA, following the guidelines proposed by Pullin and Stewart (2006). These guidelines define three steps: (1) planning the review, which consists in introducing research questions and developing a review protocol, (2) conducting the review, which includes the searching for data, the selection of relevant data (based on the definition of inclusion and exclusion criteria), assessing data quality, data extraction, and data synthesis, and (3) reporting and dissemination of the results.

This systematic review protocol was not registered in any database of systematic reviews, such as the International prospective register of systematic reviews–PROSPERO (NIHR, 2019) or the Cochrane Database of Systematic Reviews–CDSR (Cochrane, 2019), because, currently, there are no specific databases in the field of environmental sciences. The existence of such kind of databases could support the identification of subjects requiring further assessment and reduce the bias of systematic reviews in the field.

3.1. Planning the review

This step considered the definition of the research questions to be addressed in the systematic review and the elaboration of the review protocol. The review protocol is detailed in the Supplementary Material (SM). The research questions addressed in the review are the following:

- How has the scientific literature on LCSA evolved in recent years?
- Which are the main methodological approaches to conduct LCSA?
- How were the main methodological choices in each phase of LCSA dealt with in case studies?
- What are the main limitations and challenges while conducting an LCSA?

3.2. Conducting the review

The literature search was carried out by searching for relevant articles in the Scopus and the Web of Science databases. The review protocol considered search terms in the title, abstract, and keywords. Two major groups of search expressions were used. The first group consisted of the search for “Life Cycle Sustainability Assessment”, “Life Cycle Sustainability

Analysis" or their acronym, LCSA. Considering that in the early discussion of LCSA, this term was not specifically adopted, a second group of expressions was used. It consisted of a combination of the terms "Life Cycle Assessment" or LCA, "Social Life Cycle Assessment" or s-LCA or SLCA and "Life Cycle Costing" or LCC. The current LCSA review consists of a literature search for relevant studies published or in the press in peer-reviewed journals up to December 2018[2]. An initial year was not defined in the search criteria to allow considering the historical perspective of LCSA development.

The selection of articles for the review was based on the definition of the inclusion and exclusion criteria. The inclusion criteria consisted of articles published in peer-reviewed journals that have addressed simultaneously the three pillars of sustainability (environmental, economic, and social) in a life cycle perspective. After excluding duplicates, the exclusion criteria consisted of articles not written in English and gray literature (such as books, book chapters, conference papers, editorials, errata, notes, and letters). Gray literature was excluded to ensure the quality of the selected articles as such publications are usually not peer-reviewed and may represent preliminary research findings, which may reflect in high variability of its quality (Adams et al., 2017). Following this, the remaining articles were assessed independently by two of the authors[3] to exclude articles not related to LCSA or that did not address simultaneously the three pillars of sustainability. This process aimed to support greater reliability in the inclusion of articles.

Data extraction was conducted qualitatively for all the identified articles. Data synthesis consisted of the classification of the selected articles as review, viewpoint, methodological development, mixed approaches, and case studies (Table 1) and the subsequent extraction of their qualitative data. The articles falling in the categories of methodological development, mixed approaches, and case studies were further classified and discussed considering the following approaches for conducting LCSA: (1) LCSA = LCA + LCC + SLCA, (2) LCSA = new approach, and (3) LCSA as others (including the approaches LCSA = eco-efficiency + SLCA and LCSA = LCA + socioeconomic analysis). This classification is based on the study of Cinelli et al. (2013), as presented in Section 2. The review and viewpoints were not further classified because they do not propose methods to operationalize LCSA. The data synthesis highlighted the findings of mixed approaches and case studies since these articles operationalize LCSA considering real case studies. Articles under these categories were analyzed according to the phases defined in the ISO 14040:2006 standard (ISO, 2006a): goal and scope definition, LCI, LCIA, and life cycle interpretation.

3.3. Reporting and dissemination of the results

The findings of the review are presented in Section 4. The results from the application of the search and inclusion/exclusion criteria are presented, followed by a summary of how the articles on LCSA have been evolving over the years. Subsequently, all the selected articles are analyzed descriptively according to their category and according to the research questions set for this review.

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[2] The last update of the systematic review was on April 5th, 2019.

[3] All disagreements were solved by discussion between reviewers until consensus was reached.

4. Results

The search based on the review protocol resulted in a total of 319 publications in the Scopus database and 283 in the Web of Science database, totaling 602 publications. After removing duplicates (237 publications), publications falling in the following criteria were excluded: publications not written in English (9 publications), gray literature (95 publications), and articles not related with LCSA or that focused on a single pillar of sustainability (117 articles). The selection of articles is summarized in Figure 1. The data search resulted in the eligibility of 144 articles (a full list is disclosed in the SM).

4.1. Publication trends on LCSA

Evaluation of publication trends was performed based on the year of publication and the geographical location (which considered the first-author affiliation). Since the emergence of the concept of a life cycle-based tool to assess sustainability, first published by Klöpffer (2003), LCSA has been rapidly attracting interest, which reflects in an increasing trend in the number of articles focusing on this tool, as shown in Figure 2. The growth in the number of articles from 2010 onwards can be partially explained by the publication of the guidelines on SLCA (UNEP/SETAC, 2009). These guidelines consolidate the early discussions on the inclusion of social aspects in the LCA framework that began in the ’90s and was followed by several efforts in the scientific literature (Benoît et al., 2010). Similarly, the increase in the total number of articles can be partially explained by the publication of the LCSA guidelines by UNEP/SETAC (2011) and the corresponding methodological sheets for subcategories in SLCA (UNEP/SETAC, 2013).

Regarding the classification adopted in , 49 articles are classified as case studies, 33 as reviews, 33 as methodological development, 22 as mixed approach and 7 as viewpoints. Most of the selected articles (51%) are composed of reviews, methodological developments, and viewpoints, showing that LCSA is still developing its theoretical basis, as already pointed out by Zamagni et al. (2013). Even though the methodology is still at a theoretical and conceptual development level, several practitioners have already started implementing LCSA to explore its potential to measure sustainability. This trend is demonstrated by the growth in the number of case studies and mixed approaches studies in recent years (Figure 2).

Regarding the geographic distribution (Figure 3), a diversification of origins of articles (ranked by the first-author affiliation) started from 2007 onwards, when a tendency of articles from countries outside Europe starts to be noticed, which is intensified from 2012 on. The greatest number of articles are from Germany (22), followed by the United States of America (USA) (16), Italy (14), and China (13). Other countries with a relevant total number of articles in Europe are the Netherlands (10), Spain (6), and France (5). The USA and Germany present the largest number of case studies and mixed approaches (11 each), whereas conceptual contributions to the development of the LCSA methodology, represented by reviews and viewpoint articles, are led by Germany and Italy (11 each).

4.2. Review and viewpoint articles

A total of 7 articles were categorized as a viewpoint in the reviewed literature, and they were published mainly in two distinct phases. The first corresponds to the early debate on LCSA, in which the basis of the methodology was settled, focusing on the relevance of the development of a sustainability tool based on a life cycle perspective through the integration of social and economic aspects into LCA (Klöpffer, 2003) and the perspectives for its development (Klöpffer, 2006), still without using the term LCSA. In the second phase, the viewpoint articles discussed LCSA as an established methodology, focusing on aspects related to its development. This is the case of the discussion of the role of LCC as the economic pillar in LCSA (Klöpffer and Ciroth, 2011), the discussion of the development of LCSA computation systems (Marvuglia et al., 2015), and the discussion on the evolution and challenges of the development of LCSA framework (Zamagni, 2012), its limitations, and the challenges toward its operationalization (Heijungs et al., 2010; Zamagni et al., 2013).

The reviews correspond to 33 articles, from which 20 focused on the understanding of LCSA in the context of specific topics, discussing frameworks, adequacy of methods, and the state of development. Examples of topics discussed include the evaluation of life cycle thinking applied to cities (Petit-Boix et al., 2017), and the suitability of LCSA methods applied to the assessment of nanotechnologies (Meyer and Upadhyayula, 2014)–full disclosure of objects of application is presented in the SM. The remaining 13 articles present more general reviews on LCSA as a methodology, discussing related methods, such as the interaction of LCC and cost–benefit analysis (Blundo et al., 2014) or the role of economics in LCSA (Hall, 2015). From these, only Onat et al. (2017) and Tarne et al. (2017) conducted a review and discussion of the scientific literature in LCSA, but without adopting a systematic perspective.

4.3. Articles on methodological development and mixed approaches

The articles categorized as methodological development and mixed approach offer methodological contributions toward the operationalization of LCSA, and most of them fall under the approaches presented in Section 2. The few exceptions are articles that discuss broader themes, such as areas of protection (Dewulf et al., 2015), the computational structure for LCSA (Heijungs et al., 2013), the proposal of a sustainability SWOT (Strengths, Weaknesses, Opportunities, Threats) matrix (Pesonen and Horn, 2013), the role of culture as an impact indicator (Pizzirani et al., 2018; Pizzirani et al., 2014), the consideration of animal welfare into LCSA (Scherer et al., 2018), the identification of safeguard subjects and indicators for sustainability assessment (Steen and Palander, 2016), and the definition of the goal and scope phase in LCSA (Stefanova et al., 2014). It is noteworthy that articles that contribute to the LCSA methodological development, applied to case studies, were classified as mixed approaches (Table 1), and thus, are discussed in Section 4.4.

4.3.1. LCSA as the sum of LCA, LCC, and SLCA

A total of 29 articles proposed methodological development under the approach that considers LCSA as the sum of LCA, LCC, and SLCA. For example, in a broader perspective toward the implementation of LCSA, Neugebauer et al. (2015) proposed a tiered assessment, in which the three pillars of sustainability are assessed in different tiers with an increased level of completeness and a minimum number of impact assessment indicators of the three pillars to be assessed inside each tier. Other more general contributions include the proposal of economic LCA instead of the typical LCC to better reflect the impacts (Neugebauer et al., 2016; Wood and Hertwich, 2013) and the definition of LCSA frameworks for specific products or activities, such as in the cases of biodiesel (Nguyen et al., 2017a), concrete recycling (Hu et al., 2013), net-zero buildings (Hossaini et al., 2015a; Hossaini et al., 2015b), resource recovery from waste (Millward-Hopkins et al., 2018), and waste management (Menikpura et al., 2012).

Although when this approach was proposed by Kloepffer (2008), the recommendation was to perform separate assessments of LCA, LCC, and SLCA, without any aggregation of results. Most of the studies in this category discussed the integration of the pillars of sustainability–a tendency that is further discussed in Section 4.4. Such integration is like the single score concept in the environmental LCA, as it supports the prioritization of alternatives by multiple stakeholders/decision-makers and allows the comparability of different metrics. The methods that have been proposed for this purpose consist of normalization and weighting, multi-criteria decision analysis (MCDA) methods, and computational weighing through the life cycle sustainability dashboard (LCSD). An example of the weighting procedure is provided by Grubert (2017), who proposed to obtain weighting factors through declared preferences based on the questionnaires. Regarding MCDA, a great variety of methods has been proposed, such as the multi-objective optimization with multi-attribute value theory (MAVT) (Ekener et al., 2018), the analytic hierarchy process (AHP) (Azapagic et al., 2016; Ren et al., 2015; Ren et al., 2017), and data envelopment analysis (Galán-Martín et al., 2016). Concerning LCSD, it is a free software presented by Traverso et al. (2012b), in which the assessment of the economic, social, and environmental pillars is represented in a dashboard as separated assessments, and, aggregated through weighting among the indicators.

4.3.2. LCSA as a new assessment

The LCSA approach, as a new assessment, is covered by 13 articles. As defined, LCSA as a new assessment is based on a single inventory for environmental, social, and economic parameters (Cinelli et al., 2013; Kloepffer, 2008). Two main trends are evidenced in this approach. The first one is the development of characterization models (Cimprich et al., 2018; Cimprich et al., 2017; Gemechu et al., 2016; Schneider et al., 2014). The second is related to different proposals of models to obtain scores to allow the ranking of options of products or processes. These proposals include the development of multi-actor decision-making method (Ren et al., 2018), the use of fuzzy inference (Kouloumpis and Azapagic, 2018), gray relational analysis (Manzardo et al., 2012), the interval preference relation-based goal programming model (Ren, 2018), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Gumus et al., 2016; Kalbar et al., 2016; Kucukvar et al., 2014a), the development of a vector-based three-dimensional methodology (Xu et al., 2017), and the development of a novel MCDA method (Ren and Toniolo, 2018).

4.3.3. Other approaches

In total, 5 articles consider other approaches to the methodology of LCSA. LCSA, as the sum of eco-efficiency and SLCA, is found as a methodological proposal and is applied in Kurczewski and Lewandowska (2010). It consists of an eco-design procedure having the ISO/TR 14062:2002 (ISO, 2002) as guidelines. In this framework, LCA, SLCA, and LCC are methodological steps to be taken in consideration on the planning phase of the eco-design of a product. The results of such methods may lead to recommendations that support the design process.

Even though LCSA as the sum of LCA and socioeconomic analysis has been applied in several case studies by IFEU (Reinhardt, 2014; Rettenmaier et al., 2014), in the reviewed articles, it is applied in a single article (Keller et al., 2015). This approach is built upon the ISO 14040:2006 and the ISO 14044:2006 (ISO, 2006a, b) standards, and consists of performing LCA, LCC, SLCA, and barrier analysis, which consist in the assessment of possible unexpected events in the implementation of the identified scenarios. Additionally, results obtained in this methodological proposition are integrated based on a selection of scenarios considering cross-disciplinary indicators and benchmarking (Keller et al., 2015).

More recently, other approaches have been proposed, as it is the case of the life cycle sustainability unified analysis (Kua, 2017) and the modeling of the complex system approach (Wu et al., 2017). In the first approach, a model is developed to account for the role of stakeholders, rebound effects, vulnerability, and resilience, whereas the second approach makes use of the agent-based modeling to investigate temporal, spatial, and behavioral dynamics in the LCI phase.

4.4. Articles on mixed approaches and case studies

A total of 71 articles were classified as mixed approaches and case studies. Most articles (54) adopted the approach of LCSA = LCA + LCC + SLCA, while 13 considered LCSA = new and 4 adopted other approaches (Table 2). The latter includes one article presenting the sum of eco-efficiency and SLCA (Kurczewski and Lewandowska, 2010), and one article for the approach of LCSA as the sum of LCA and socioeconomic analysis (Keller et al., 2015), that were also discussed in articles classified as methodological development. It also includes a different methodological approach, applied by Onat et al. (2016b) and Onat et al. (2016c), consisting of a temporal dynamic LCSA. The assessment of articles that were classified as mixed approaches or case studies follows the structure set by ISO 14040:2006 (ISO, 2006a), which is adopted by all articles, except for Manzardo et al. (2012)[4].

4.4.1. Goal and scope definition

This Section presents how the goal and scope definition phase has been addressed in the reviewed articles, focusing on the theme of the study, the delimitation of the system boundary, the multi-functionality procedures, and the modeling approach (attributional or

[4] In Manzardo et al. (2012), a life cycle inventory is not compiled, and therefore, this article is not considered in the assessment of the life cycle inventory analysis.

consequential). The reviewed articles are divided into the assessment of products (63%), processes (23%), and services (14%). A variety of sectors has been assessed in the scientific literature, but the energy, automotive, and construction sectors take the lead (Figure 4).

Regarding the system boundaries, 38.0% considered a cradle-to-grave assessment, 38.0% a cradle-to-gate, 7.0% a gate-to-gate, 8.5% a gate-to-grave, and 1.4% adopted a cradle-to-cradle perspective. It is noteworthy that 7.0% of the studies (5 articles) did not define the system boundaries, being all of them adopting the approach of LCSA as a new assessment (Kalbar et al., 2016; Kucukvar et al., 2014a; Manzardo et al., 2012; Onat et al., 2016a; Ren and Toniolo, 2018) to rank options of processes or products.

Regarding the modeling approach, most of the studies applied an attributional approach (96%), whereas consequential modeling was used in only 3% of studies (Keller et al., 2015; Nguyen et al., 2017b). The other 1% corresponds to the work of Corona and San Miguel (2018), which made use of both attributional and consequential modeling approaches. Articles assessing the geopolitical supply risk or the economic resource scarcity potential of resources (Cimprich et al., 2018; Cimprich et al., 2017; Gemechu et al., 2016; Gemechu et al., 2017; Helbig et al., 2016; Schneider et al., 2014) do not identify the modeling approach, and it is assumed as having adopted the attributional approach since they do not model changes resulting from a change in demand of the functional unit.

The multi-functionality is addressed in 9 articles. The strategies adopted to deal with multi-functionality follows the typical ones of the environmental LCA, such as system expansion (Menikpura et al., 2012), allocation by mass, volume, economic value, or other criteria (Aziz et al., 2016; Chen and Holden, 2018; Contreras-Lisperguer et al., 2018; Ekener et al., 2018; Nguyen et al., 2017b; Vinyes et al., 2013; Wang et al., 2017; Wulf et al., 2017). However, it is not clear whether the criteria are applied only to the environmental data or also to social and economic data. Only Vinyes et al. (2013) explicitly indicated that the same allocation procedure (based on the economic value) was applied to the environmental, social, and economic aspects.

4.4.2. Life cycle inventory analysis

The LCI is the phase in which input and output data of the system under analysis are collected and/or calculated. In the LCSA = new approach, a single inventory is compiled integrating the environmental, social, and economic indicators, that is translated as impact categories in the LCIA (Cinelli et al., 2013). In the articles that adopt this approach, the definition of a single inventory is conducted in two different ways. In the first way, articles that obtain a single index to allow the comparison of the sustainability of a product or process apply different methods considering the opinion of stakeholders (Kalbar et al., 2016; Khalili et al., 2013; Kucukvar et al., 2014a; Manzardo et al., 2012; Onat et al., 2016a; Ren et al., 2015; Ren and Toniolo, 2018). In the second way, the assessment of the criticality of resources is achieved through the development and application of characterization models (Cimprich et al., 2018; Cimprich et al., 2017; Gemechu et al., 2016; Gemechu et al., 2017; Helbig et al., 2016; Schneider et al., 2014).

Regarding the source of data, the articles use both primary and secondary data. The main sources of the primary data are field observation, laboratory analysis results, and interviews. The interviews are particularly used to obtain data for the assessment of social aspects. For the secondary data, the main sources are commercial databases (for the environmental and social assessments), scientific literature, and commissioned reports. The secondary sources of data are the most used in all pillars of sustainability and are considered as the exclusive source of data in 45 articles for the environmental pillar, 42 for the social pillar, and 47 for the economic pillar. In contrast, primary data is used in 6, 14, and 8 articles, respectively, for the environmental, social, and economic pillars. The simultaneous use of primary and secondary data is higher in the assessment of the environmental aspects (16 articles) when compared with the social and economic pillars (6 and 9 articles, respectively).

Different databases are considered to establish environmental, social, and economic LCI. The Ecoinvent database[5] (Ecoinvent, 2018; Wernet, 2016) is the most used commercial database for the environmental data, is reportedly used in 35 articles. Other databases referred for the environmental data is the Gabi database (PE International, 2018) used in 3 studies (Schau et al., 2012; Stark et al., 2017; Wang et al., 2018) and the BUWAL 250 database (SVI, 1996) used in the research of Menikpura et al. (2012). The commercial databases for social data acquisition are also considered, such as the Social Hotspots Database (SHDB) (Norris et al., 2013; Norris and Norris, 2015)–the most used one (in 8 articles). Other databases considered to perform the social assessment is the Life Cycle Working Environment (Knüpffer et al., 2016), applied in the studies of Martínez-Blanco et al. (2014) and Chen and Holden (2018), and the Product Social Impact Life Cycle Assessment (PSILCA, 2018), used in the research of Halog and Manik (2011). For the economic pillar of sustainability, the use of commercial databases was not identified in the articles analyzed. Finally, another approach to compile the LCI is adopted in Onat et al. (2016b) and Onat et al. (2016c), in which dynamic modeling is considered. In these studies, the inventory data is elaborated to account for the causal links between the inventory variables.

4.4.3. Life cycle impact assessment

In the LCIA phase, the inventory data are translated into impacts. This Section evaluates the mandatory steps considered for this phase in LCA by the ISO 14044:2006 (ISO, 2006b). These steps are: (1) the selection of impact categories, category indicators, and characterization models, (2) classification (which consists of assigning LCI results to the impact categories according to their known potential effects), and (3) characterization (calculating the category indicator results quantifying the contributions from the inventory flows to the different impact categories).

Several methods for the environmental impact assessment have been published since the first one appeared in 1984 (Rosenbaum et al., 2018), which led to a determination of the environmental impact categories and characterization factors because of the choice of the existing methods. In the reviewed articles, 50 applied LCIA methods that are well known in the scientific literature and their respective characterization factors. From these, the most used are the CML (CML, 2016) and the ReCiPe methods (Goedkoop et al., 2009) in different versions (21 and 19 articles, respectively), besides the fact that some articles make use of more than one method for comparison of the impact results from different methods. From the remaining articles, 17 adopted other methods, e.g., the carbon footprint, and 4 did not disclose the

[5] Several versions have been used in the articles reviewed. For the sake of simplicity, the Ecoinvent version 3 and the Ecoinvent website are referenced.

adopted methods. From the articles making use of well-known LCIA methods, the majority corresponds to the LCSA = LCA + SLCA + LCC approach (45 articles), 3 to the LCSA = new approach (Cimprich et al., 2018; Gemechu et al., 2017; Ren et al., 2015), and 2 to LCSA as other (Keller et al., 2015; Touceda et al., 2018).

Considering the social pillar of sustainability, different methods or frameworks have been proposed for SLCA (Dreyer et al., 2006; Franze and Ciroth, 2011; Hunkeler, 2006; UNEP/SETAC, 2009) and, currently, there is no harmonized method or framework. That translates into some uncertainty in requirements for the impact categories to be addressed in SLCA. A variety of impact indicators are used to assess the social pillar, such as the stimulation of sustainable behavior, human health, fire resistance, or the number of fatalities, among others (Gencturk et al., 2016; Hossaini et al., 2015b; Kalbar et al., 2016; Onat et al., 2016b). The lack of uniformity in these indicators makes it difficult to compare methods and results among similar processes and/or products. Other indicators used are the social themes and the Social Hotspot Index–both available through the use of the SHDB (Norris and Norris, 2015; SHDB, 2018), which is applied with modifications in 8 articles (Corona and San Miguel, 2018; Ekener et al., 2018; Manzardo et al., 2012; Martínez-Blanco et al., 2014; Reuter, 2016; Schau et al., 2012; Touceda et al., 2018; Wulf et al., 2017). The assessment system recommended by SETAC (UNEP/SETAC, 2009, 2013), based on the use of impact categories and subcategories defined per stakeholder type, is used in a total of 17 articles.

Regarding the economic pillar of sustainability, there is no impact assessment phase because all data are reported in monetary units (Swarr et al., 2011). All the reviewed articles evaluate the economic pillar adopting an LCC perspective. The LCC is classified as conventional, environmental, and societal, depending on the type of costs and benefits assessed (Hunkeler et al., 2008; UNEP/SETAC, 2011). The conventional LCC considers private costs and benefits only. The environmental LCC comprises both the private and relevant external costs and benefits, i.e., externalities are internalized in monetary units. The societal LCC includes all private and external costs and benefits, i.e., it includes all costs that are relevant to the stakeholders, somehow affected through externalities, covering costs covered by anyone in the society whether today or in the long-term.

From the total articles classified as mixed approaches and case studies, most of the evaluated articles performed the conventional LCC (61 articles), considering the impact categories as the internal economic aspects, such as capital, operational costs, and revenues. The method of assessment based on the conventional LCC often makes use of the methods to appraise the value of an investment, such as net present value, payback time, cost-benefit analysis, and the internal rate of return. It is noteworthy that some articles performing the conventional LCC often include a contribution to the economic indicators, such as the Herfindahl–Hirschman index, gross domestic product, and the human development index.

An environmental LCC was carried out in 5 articles (Foolmaun and Ramjeawon, 2013; Jin et al., 2017; Onat et al., 2014b; Ribeiro et al., 2018; Vinyes et al., 2013). The cost related to carbon dioxide (CO_2) emissions was the most covered aspect through different metrics. In these studies, the environmental LCC was carried out through the consideration of mitigation cost (Vinyes et al., 2013), avoiding CO_2 emissions (Ribeiro et al., 2018) and total carbon credits (Jin et al., 2017). In the study by Foolmaun and Ramjeawon (2013). The damage costs were calculated based on the total emissions of pollutants released annually through the estimates presented in the ExternE project (Bickel and Friedrich, 2004; Hunkeler et al., 2008). In Onat et al. (2014b), the environmental LCC is based on the air emission costs of externality damages related to the release of selected pollutants.

Finally, societal LCC was presented in 5 articles. Dobon et al. (2011) and Khalili et al. (2013) considered different stakeholders and aspects to assess the costs of externalities of their case studies, such as the occurrence of fatalities and social welfare, respectively. Reuter (2016) considered different types of emissions and lost resources (such as raw materials and energy resources), while Settembre Blundo et al. (2018) and Garcia–Muiña et al. (2018) assessed the willingness to pay according to the EPS 2000 method (Steen, 1999).

The current immature state of the LCSA methodology increases the complexity of the results, hampering its easy communication. To improve the communication of LCSA results, UNEP/SETAC (2011) advised that plain results for the three pillars should be presented, and the results should not be recommended against any aggregation and weighting. This recommendation was also provided by Kloepffer (2008) in the earlier stage of the development of LCSA. However, only 32 articles presented results for each pillar of sustainability individually, against 39 articles that integrated the results of the three pillars. The integration aims to create a single unit of measure or to rank among different sustainability pillars, and is described by different nomenclatures, such as sustainability score (Akber et al., 2017; Atilgan and Azapagic, 2016; Aziz et al., 2016; Chen and Holden, 2018; De Luca et al., 2018), geopolitical supply risk (Cimprich et al., 2018; Cimprich et al., 2017; Gemechu et al., 2016; Gemechu et al., 2017; Helbig et al., 2016), and sustainability index (Akhtar et al., 2017; Ekener et al., 2018; Hossaini et al., 2015b; Nguyen et al., 2017b; Reddy et al., 2018; Zhou et al., 2007; Zortea et al., 2018), among others. Different methods are available to perform such integration (), such as using: (1) normalization, weighting, and aggregation, sequentially to create a single score; (2) characterization models; (3) MCDA methods.

The calculation of a single score through sequential normalization, weighting, and aggregation of sustainability pillars based on a weighted sum is adopted by 4 articles (Akber et al., 2017; Aziz et al., 2016; Wulf et al., 2017; Zhou et al., 2007). The proposal and use of the characterization models to integrate all the sustainability pillars was adopted by 6 articles that follow the LCSA = new approach (Cimprich et al., 2018; Cimprich et al., 2017; Gemechu et al., 2016; Gemechu et al., 2017; Helbig et al., 2016; Schneider et al., 2014). Another procedure is the use of MCDA methods since they allow the assessment of the multiple objectives and trade-offs between the three pillars. In total, 20 articles made use of MCDA methods, AHP as the most used. AHP is used to create a pairwise comparison to obtain weights mathematically. The weighting based on AHP may consider different weighting schemes or support the comparison of options based on the judgment of the experts, decision-makers, or the stakeholders.

4.4.4. Life cycle interpretation

The aspects investigated in this review regarding the life cycle interpretation focus on some of the recommendations of the guidelines of UNEP/SETAC (2011) to assess data quality and reliability through sensitivity and uncertainty analyses. The evaluation of the reviewed articles demonstrates that only 16 conducted sensitivity analysis, 3 uncertainty analysis, and 4 conducted both analyses.

Among the studies conducting sensitivity analysis, most of them (9) used this procedure for testing different weighting schemes among the three pillars of sustainability (Akhtar et al., 2017; Atilgan and Azapagic, 2016; Foolmaun and Ramjeawon, 2013; Hossaini et al., 2015b; Kucukvar et al., 2014b; Reddy et al., 2018), among the impact categories (Ren et al., 2015; Ren and Toniolo, 2018), or both (Mahbub et al., 2018). Wulf et al. (2017) also assessed the effect of both different weights among the three pillars as well as different normalization (the difference between the minimum and maximum value, the ratio of minimum and maximum values, and ranking) and aggregation methods (linear and geometrical aggregation). Other alternatives to conduct sensitivity analysis consist of changing parameters one-factor-at-a-time (Aziz et al., 2016; Balasbaneh et al., 2018; Moriizumi et al., 2010; Nguyen et al., 2017a; Ostermeyer et al., 2013; Sou et al., 2016), changing the impact assessment method (Li et al., 2018) or applying a Monte Carlo analysis (Onat et al., 2014a, 2016b). Ekener et al. (2018) performed three sensitivity analyses: exclusion of LCC from the LCSA results, change in system boundaries, and application of uncertainty ranges in the SLCA results. However, only in the study conducted by Moriizumi et al. (2010) the impact on social aspects is considered in the sensitivity analysis through the observation of changes in the employment rate. The uncertainty analysis is assessed through the consideration of uncertainty ranges in results or parameters (Ekener et al., 2018; Mahbub et al., 2018), Monte Carlo simulations (Contreras-Lisperguer et al., 2018; Gemechu et al., 2016; Onat et al., 2016b), and the use of intuitionistic fuzzy set (Onat et al., 2016a)[6].

5. Discussion

Even though LCSA is still not as widespread as LCA, the interest in this methodology is increasing over the years, as shown in Figures 2 and 3. However, LCSA is still on a relatively immature state of development, and several challenges remain in its consistent operationalization, making it difficult to obtain reliable and comparable results. This is mainly because of the complexity of LCSA–the existence of a variety of metrics and the different levels of maturity in the assessment of the three sustainability pillars. Moreover, each LCSA phase presents specific challenges and issues that are addressed below.

In the goal and scope definition phase, the definition of coherent system boundaries is the first challenge for the operationalization of LCSA, despite the approach adopted. The system boundaries of the different sustainability pillars may not be always identical because they may be related to different aspects over the life cycle of the object of study (e.g., the physical life cycle or the conceptual aspects over the life cycle), which reflects in the use of different metrics. For instance, LCA is likely to comprise material fluxes, SLCA may present qualitative indexes, and LCC may include non-tangible activities, such as marketing costs. Another cause of inconsistency of the system boundaries is the lack of background data to consider a life cycle perspective for the social and economic pillars. In fact, in most of the articles reviewed, a life cycle perspective is mostly adopted for the environmental pillar, whereas social and economic aspects are often only evaluated for the foreground system. This leads to different completeness levels in the three pillars that can be more problematic if the hotspots are in the background system. Moreover, the definition of the consistent system boundaries is particularly critical to avoid the possibility of double counting impacts, in both financial and physical terms across the pillars. Despite the importance of this issue, it is often

[6] The methods to conduct the uncertainty analysis are not disclosed in Sou et al. (2016).

undervalued in the scientific literature. In the reviewed articles, only Martínez-Blanco et al. (2014) defined the system boundaries of the three pillars in detail and assessed the consistency among them.

The allocation procedures in the multi-functional systems should also be done consistently across LCA, LCC, and SLCA. However, the application of allocation criteria based on the physical or economic relationships, as recommended in ISO 14044:2006 (ISO, 2006b), may not be completely feasible in the assessment of social aspects because of the use of semi-quantitative and qualitative indicators. It is noteworthy that even though the existing guidelines for SLCA and LCSA (UNEP/SETAC, 2009, 2011, 2013) support the use of allocation procedures, some authors speak in the favor of an assessment of social impacts not based on a product perspective, but rather in the conduct of the company producing the product, because the focus on a product can be a source of bias (Zamagni et al., 2011). In this case, the allocation is not required even when the company produces multiple products. In the reviewed literature, just a few cases of multi-functionality are presented, and most of them are not explicit if the procedure was also applied to economic and social data.

In the LCI phase, different procedures can be adopted depending on the approach, such as data are may be collected separately for LCA, SLCA and LCC; or environmental, social and economic data are collected in a consistent way to compile a single inventory. Regardless of the approach, several issues arise in LCI, partly because of its interaction with the next step, LCIA. The lack of harmonization of methods for LCIA leads to a lack of consensus on defining the impact categories to be assessed, and consequently, the corresponding inventory data. This occurs particularly for the economic and social pillars, for any of the approaches.

A critical aspect of LCI is the lack of secondary social and economic data. The fact that the current social and economic databases are still not as comprehensive and widespread as the environmental databases lead to a high dependency of company-related data to assess these pillars. Even though the use of primary data is highly encouraged in life cycle thinking, it often fails in providing information about aspects not directly related to the company or enterprise, not allowing the consideration of life cycle perspectives for the impacts. Although social databases are emerging, there is a different level of development of them when compared with the environmental databases, being the latter more robust and representative of several and different economic sectors. Regarding the economic databases, only databases for the calculation of externalities are available to date, even though a cost-based perspective is also possible when using input-output databases.

In the LCIA phase, as already mentioned, there are no methods internationally harmonized for assigning the inventory data into impact categories for social and economic pillars separately, or in an integrated way in a process-based perspective. In the LCSA = LCA + SLCA + LCC approach, the LCIA phase faces challenges that are inherent to each of the partial methods (LCA, SLCA, and LCC) individually, and to the interactions between them. The application of SLCA is currently the most challenging for the practitioner because it is still under debate and development in the scientific literature. The LCC puts also some challenges; for instance, it differs from LCA in the time perspective. In LCA, the time is related to a total amount of total material fluxes, which can be aggregated through the life cycle, while in an LCC, the monetary aspects vary in a yearly basis if a discount rate is considered, which do not allow a static perspective of impacts. Besides, in LCC, it is also necessary to define which perspective is relevant to be considered in the context of an LCSA (conventional, environmental, or societal).

Still on this approach, the integration of the results of LCA, SLCA, and LCC is performed in several of the reviewed articles, following different methods. The most common methods consist of the use of a weighting scheme based on MCDA methods (as detailed in Table 3), or in the use of the typical normalization, aggregation, and weighting of results. For the use of MCDA methods, in most of the reviewed studies, the selection of method is not clear, which may also lead to bias. The bias is particularly critical when the methods are based on the opinions of individuals, such as in the studies that create indexes based on the opinion of stakeholders or expert judgment. Therefore, good practice could be the use of more than one method to obtain results that are more reliable. Regarding the normalization, aggregation, and weighting, the selection of different methods can affect the integrated results obtained (Wulf et al., 2017). Several authors have pointed out that weighting among the pillars or weighting among the impact categories may induce bias according to the different perspectives of decision-makers or stakeholders, even when it is based on empirically grounded data about societal preferences (Ekener et al., 2018; Foolmaun and Ramjeawon, 2013).

In the approach of LCSA = new, the LCIA is currently conducted based on the characterization methods or methods to rank across the alternatives. In the first group, the articles present characterization methods that integrate simultaneously the environmental, social, and economic indicators. However, these methods have a limited scope of application because their use is restricted to the application for which they were developed–namely the assessment of raw materials and their geopolitical supply risk or economic resource scarcity potential. In the second group, the proposed methods are all based on MCDA methods that rank experts' or stakeholders' opinions. Even though articles in this group support decision-making by ranking options, there is no full disclosure of the impacts of the object of the assessment. Therefore, it necessary to develop characterization methods that ensure their use to other objects of study to test and improve their applicability. In the case of MCDA methods, their use should be more transparent and used in a way that allows the definition of impacts, rather than solely ranking options. Besides, to ensure more transparency and robustness of results, the use of more than one MCDA method should be considered.

Inside the life cycle interpretation phase of the LCSA results, sensitivity and uncertainty analyses are still not fully explored and discussed in the reviewed articles. This matter is particularly challenging while assessing social aspects because in several case studies, the social issues are addressed qualitatively. Besides, the sensitivity of economic aspects is still poorly explored. The possibilities of further research in this matter are the evaluation of how changes in discount rates and project timeframes should be considered in an LCSA study. Other aspects, not covered in the current interpretation of the results, are the interactions of the three sustainability pillars and the assessment of rebound effects.

6. Final remarks

This study sought to offer a systematic review of the current state of development of LCSA in the scientific literature, focusing on its operationalization. It shows that the number of articles considering LCSA is growing over the years with an increasing diversification of countries of origin. It also identified that there are three main groups of LCSA approaches: (i) LCSA = LCA + LCC + SLCA, (ii) LCSA = new, and (iii) other. Today, the first approach is the most common one because it is easier to apply than the others, as LCA, SLCA, and LCC are methodologies that have been established individually. However, they present different degrees of methodological development maturity, and thus, they are often not treated with the same level of detail and consistency in terms of methodological choices (e.g., system boundaries, allocation procedures, or data quality), even in the same case study.

Different methods have been suggested to operationalize LCSA inside the different approaches, including the proposals of models to integrate the three pillars, the development of characterization models, frameworks to rank over options, and the use of system dynamics modeling. Over them, the use of MCDA methods is particularly widespread. MCDA seems like a promising tool to address sustainability problems because of the different metrics involved and the need to account for multiple stakeholders. However, more studies considering the interactions of the three pillars of sustainability and multi-scale (temporal and geographical) perspectives are needed to support the understanding of sustainability in a more holistic way.

From the review performed, it is possible to infer that the central challenge toward a more robust LCSA methodology is the need of its harmonization. The harmonization is a starting point, from which a clear definition of what should be expected from an LCSA study would emerge, supporting the definition of the impact categories to be addressed. Today, the lack of harmonization led to the use of a variety of impact categories that differ across the studies and do not allow comparison among them. Other challenges for the operationalization of LCSA also arise, such as the definition of coherent system boundaries, the creation of databases that allow a life cycle perspective in the social and economic pillars, the development of impact assessment methods, and methods to conduct sensitivity and uncertainty analysis. Additionally, the communication strategies for the dissemination of the results should be improved, allowing the identification of the interaction of the sustainability pillars and the possible interactions between them. Finally, further case studies are necessary for different sectors to increase the discussion on the emerging challenges, and to offer guidance in novel strategies to assess sustainability through LCSA.

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Figure 1

Figure 2: Total LCSA articles and per category.

Figure 3: Geographic distribution of the articles (ranked by first author affiliation).

Figure 4: LCSA case studies per sector. Note: in Cimprich et al. 2018, two case studies are presented, which are represented separately.

Table 1: Article categories.

Category	Description
Review	A publication that summarizes the state of understanding and operationalization of LCSA
Viewpoint	A short publication that focuses on key challenges, issues or developments
Methodological development	A publication that recommends methods for LCSA operationalization
Mixed approach	A publication that proposes and applies a method to a case study
Case study	A publication that applies LCSA in the assessment of a product, process or service

Table 2: Classification of adopted LCSA approaches in case studies and mixed approached articles.

Approach	Sub-classification		Reference
LCSA = LCA + LCC + SLCA	Integration of sustainability pillars	Using MCDA	Akhtar et al. (2017); Atilgan and Azapagic (2016); De Luca et al. (2018); Ekener et al. (2018); Foolmaun and Ramjeawon (2013); Hossaini et al. (2015b); Kucukvar et al. (2014b); Mahbub et al. (2018); Onat et al. (2016d); Opher et al. (2018); Reddy et al. (2018); Sou et al. (2016); Wang et al. (2017)
		Other methods	Akber et al. (2017); Aziz et al. (2016); Nguyen et al. (2017b); Nzila et al. (2012); Ostermeyer et al. (2013); Ribeiro et al. (2018); Schau et al. (2011); Stamford and Azapagic (2014); Traverso et al. (2012a); Vinyes et al. (2013); Wulf et al. (2017); Zhou et al. (2007); Zortea et al. (2018)
	Individual assessment of sustainability pillars		Balasbaneh et al. (2018); Beery and Repke (2010); Chen and Holden (2018); Contreras-Lisperguer et al. (2018); Corona and San Miguel (2018); Dobon et al. (2011); Dong and Ng (2016); Garcia-Muiña et al. (2018); Gencturk et al. (2016); Hannouf and Assefa (2017); Huang and Mauerhofer (2016); Jin et al. (2017); Li et al. (2018); Ma et al. (2018); Martínez-Blanco et al. (2014); Menikpura et al. (2012); Moriizumi et al. (2010); Onat et al. (2014a, 2014b); Reuter (2016); Settembre Blundo et al. (2018); Stamford and Azapagic (2012); Stark et al. (2017); Touceda et al. (2018); van Kempen et al. (2017); Wang et al. (2018); Yu and Halog (2015); Zajáros et al. (2018)
LCSA = new	Criticality of resources		Cimprich et al. (2018); Cimprich et al. (2017); Gemechu et al. (2016); Gemechu et al. (2017); Helbig et al. (2016); Schneider et al. (2014)
	Comparison of options		Kalbar et al. (2016); Khalili et al. (2013); Kucukvar et al. (2014a); Manzardo et al. (2012); Onat et al. (2016a); Ren et al. (2015); Ren and Toniolo (2018)
Other approaches	LCSA = LCA + socioeconomic analysis		Keller et al. (2015)
	LCSA = Eco-efficiency + SLCA		Kurczewski and Lewandowska (2010)
	System dynamic modeling		Onat et al. (2016b); Onat et al. (2016c)

Table 3: Methods adopted towards the integration of the three pillars of sustainability.

Approach	Sub-classification	Reference	Method
LCSA = LCA + LCC + SLCA	Using MCDA	Akhtar et al. (2017)	Emergy synthesis and weighting based on the analytical hierarchy process (AHP)
		Atilgan and Azapagic (2016)	Weighting based on multi-attribute value theory (MAVT)
		De Luca et al. (2018)	Weighting based on AHP
		Ekener et al. (2018)	Monetary weighting (Environmental Priority Strategies[1] and Ecovalue[2]) and MAVT
		Foolmaun and Ramjeawon (2013)	Weighting based on MAVT
		Hossaini et al. (2015b)	Weighting based on AHP
		Kucukvar et al. (2014b)	Weighting based on stochastic compromise programming
		Mahbub et al. (2018)	Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE)
		Opher et al. (2018)	Based on AHP
		Reddy et al. (2018)	Integrated Value Model for Sustainable Assessment[3]
		Sou et al. (2016)	Weighting based on AHP
		Wang et al. (2017)	Single-objective optimization
	Other methods	Akber et al. (2017)	Weighted aggregated function based on Díaz-Balteiro and Romero (2004)
		Aziz et al. (2016)	Normalization and weighting
		Nguyen et al. (2017a)	Based on the development of the Inclusive Impact Index
		Nzila et al. (2012)	Normalization
		Ostermeyer et al. (2013)	Pareto optimization
		Ribeiro et al. (2018)	Social return on investment
		Schau et al. (2011)	Life Cycle Sustainability Dashboard
		Stamford and Azapagic (2014)	Summed rank analysis
		Traverso et al. (2012a)	Life Cycle Sustainability Dashboard

Approach	Sub-classification	Reference	Method
		Vinyes et al. (2013)	A method based on the calculation of sustainability factors
		Wulf et al. (2017)	Normalization, weighting, and aggregation
		Zhou et al. (2007)	Weighted sum method
		Zhou et al. (2012)	Life Cycle Sustainability Dashboard
LCSA = new	Geopolitical supply risk/ Economic resource scarcity potential	Cimprich et al. (2018); Cimprich et al. (2017); Gemechu et al. (2016); Gemechu et al. (2017); Helbig et al. (2016); Schneider et al. (2014)	Development of characterization methods
	Comparison of options	Kalbar et al. (2016)	Based on the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)
		Kucukvar et al. (2014a)	Based on a fuzzy MCDA method including TOPSIS
		Manzardo et al. (2012)	Based on grey relational analysis
		Onat et al. (2016a)	A method based on Intuitionistic fuzzy and TOPSIS
		Onat et al. (2016d)	Based on compromise programming
		Ren et al. (2015)	Based on AHP and the VIKOR method
		Ren and Toniolo (2018)	Based on the decision-making trial and evaluation laboratory (DEMATEL) and interval evaluation based on distance from the average solution (EDAS)
		Khalili et al. (2013)	Based on the proposition of a multi-criteria decision tool based on stakeholders' score of alternatives

1: Steen (1999).

2: Ahlroth and Finnveden (2011).

3: Translated from the original 'Modelo Integrado de Valor para una Evaluación Sostenible' – MIVES.

Highlights

1. There are several approaches to conduct LCSA
2. LCSA = LCA + LCC + SLCA is the most used approach
3. Multi-criteria decision analysis (MCDA) methods are widely used to assess LCSA
4. Methodological challenges for operationalization of LCSA are identified

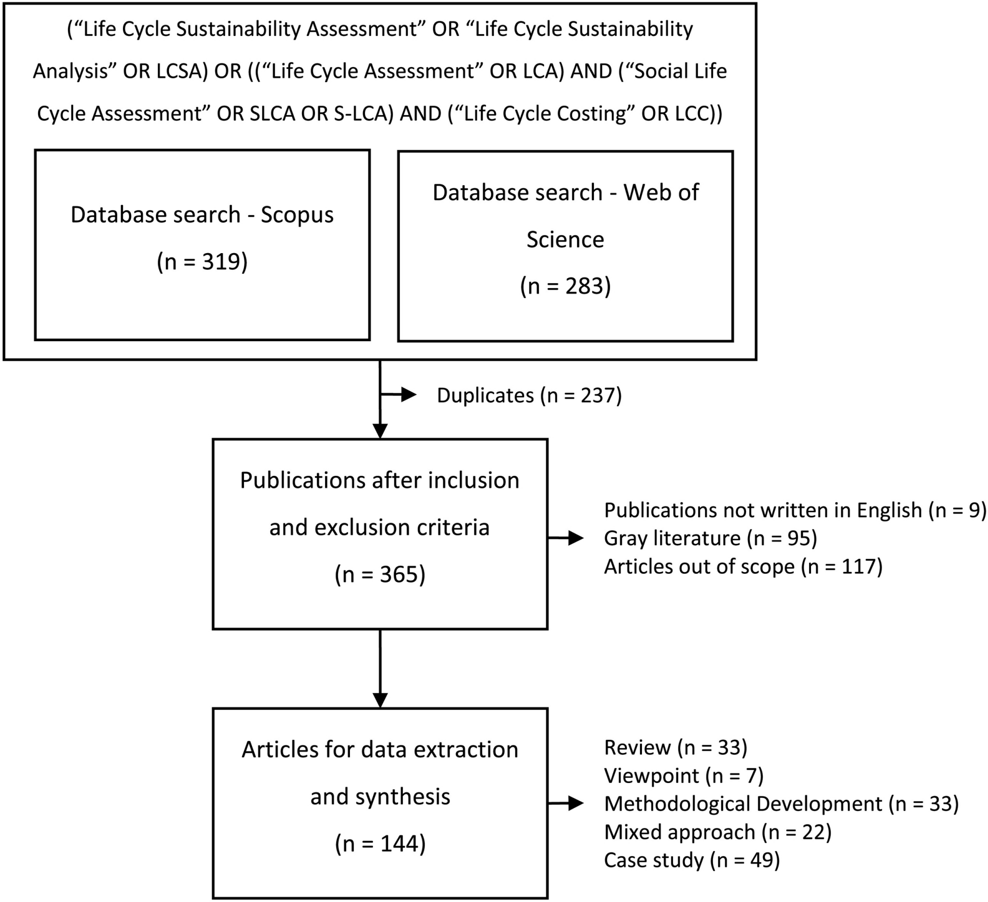
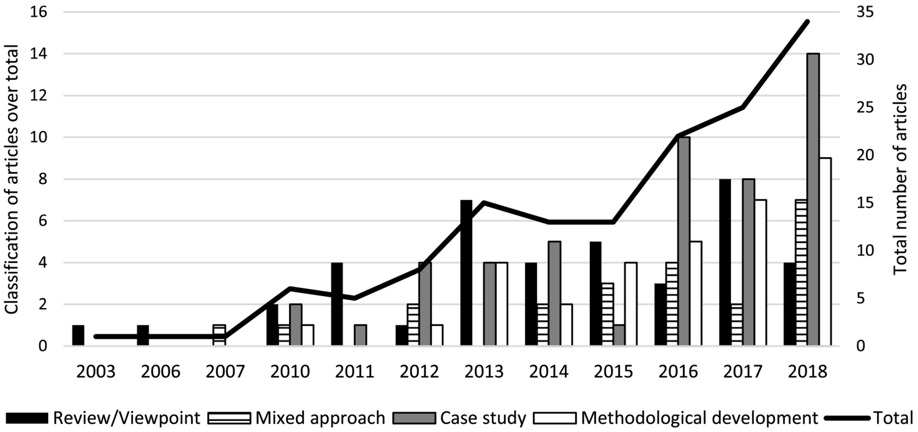

("Life Cycle Sustainability Assessment" OR "Life Cycle Sustainability Analysis" OR LCSA) OR (("Life Cycle Assessment" OR LCA) AND ("Social Life Cycle Assessment" OR SLCA OR S-LCA) AND ("Life Cycle Costing" OR LCC))
Database search - Scopus (n = 319)
Database search - Web of Science (n = 283)
Duplicates (n = 237)
Publications after inclusion and exclusion criteria (n = 365)
Publications not written in English (n = 9)
Gray literature (n = 95)
Articles out of scope (n = 117)
Articles for data extraction and synthesis (n = 144)
Review (n = 33)
Viewpoint (n = 7)
Methodological Development (n = 33)
Mixed approach (n = 22)
Case study (n = 49)

Figure 1



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Mixed approach
Case study
Methodological development
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Figure 2

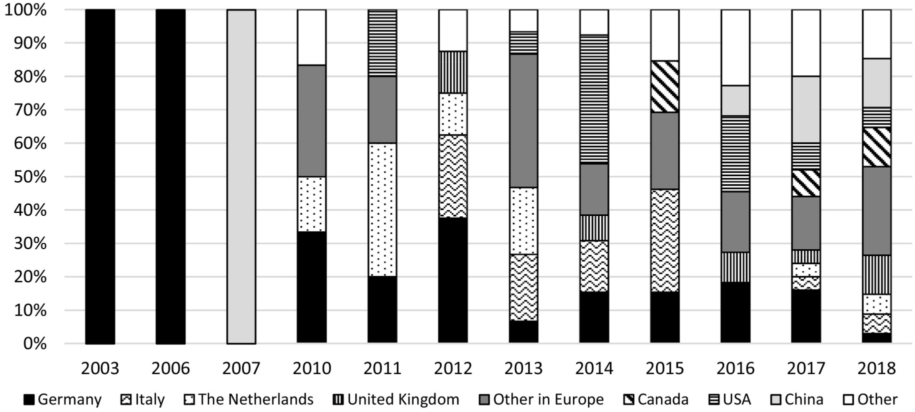
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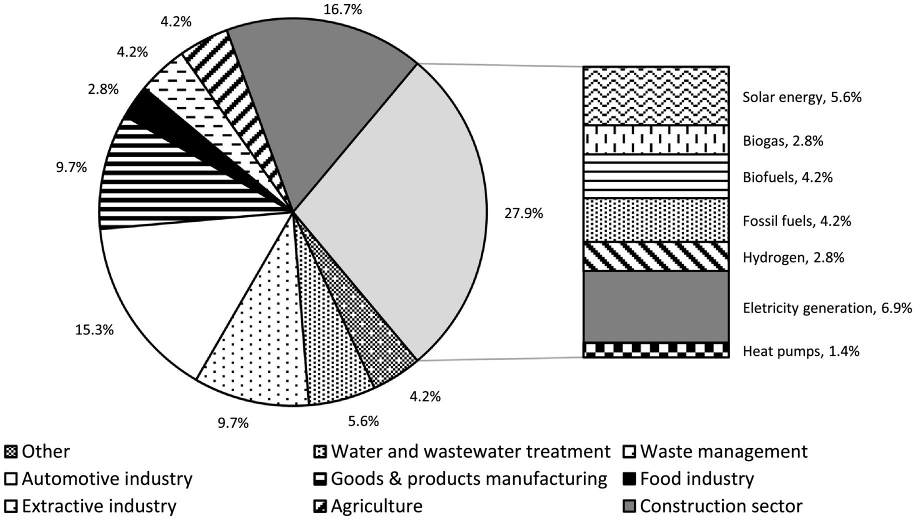
Figure 3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Biofuels, 4.2%
Fossil fuels, 4.2%
Hydrogen, 2.8%
Eletricity generation, 6.9%
Heat pumps, 1.4%
Other
Water and wastewater treatment
Waste management
Automotive industry
Goods & products manufacturing
Food industry
Extractive industry
Agriculture
Construction sector

Figure 4