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Life Cycle Sustainability Assessment (LCSA): A comprehensive overview of existing integrated approaches to LCA, S-LCA, and LCC

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ABSTRACT
Life Cycle Sustainability Assessment (LCSA) is emerging as a robust framework for integrated impact assessment across environmental, social, and economic dimensions, addressing the growing complexity of today's sustainability challenges. It consists of the combination of three different analyses: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social LCA (s-LCA). These methodologies have different technical maturity and specific peculiarities in the outcome. Hence, it is necessary to integrate different aspects of various techniques, combining both quantitative and qualitative data. The aim of this study is to provide an accurate and accessible overview of the various possible approaches for implementing a rigorous and integrated LCSA. Furthermore, the authors propose a clear and comprehensive classification of the major methods. Through a rigorous review process, a total of 66 papers were selected and analyzed, each simultaneously applying the three components of LCSA. The various integration methods were then aggregated into different categories, which are: (i) sequential analysis of LCA, LCC, s-LCA; (ii) graphical representation approaches; (iii) integration based on Multi-Criteria Decision Analysis (MCDA); and (iv) tailored ranking methods and metrics.

Keywords: Life Cycle Sustainability Assessment; Life Cycle Assessment; Life Cycle Costing; Social Life Cycle Assessment

1. Introduction

The concept of sustainability has varied many times across countries, contexts, and years, but in literature it is possible to find some milestones. Fundamental was the Brundtland Report "Our Common Future", which in 1987 stated that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Sustainability comprises three pillars: Environment, Economy, and Society (Purvis et al., 2019). The multidimensionality of sustainability, with environmental, economic, and social aspects has been explored with the concept of Triple Bottom Line (TBL) (Pope et al., 2004). The increasing need to assess the sustainability of products, services, and technologies leads to the development of various methods. Sustainability nowadays requires comprehensive assessment methods to ensure overall evaluation of environmental, social, and economic impacts. In this perspective was born the Life Cycle Thinking (LCT) approach, an analytical approach to a product or a service to assess its environmental, economic, and

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social impacts throughout its life cycle. Among the assessment methods available in LCT, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (s-LCA) address the environmental, economic, and social pillars of sustainability, respectively, with LCA being particularly prevalent in decision-making contexts that involve operational, tactical and strategic decisions, or as a tool for labeling products in the marketplace and developing policies (Sonnemann et al., 2017). Many authors (e.g. Sala et al., 2013) suggested that, for a comprehensive approach to sustainability, it is necessary to aggregate the existing life cycle thinking tools. This integration is known as the Life Cycle Sustainability Assessment (LCSA), a tool for organizing both economic, environmental, and social impact data within a combined architecture. It provides a well-rounded representation of impacts across the life cycle and facilitates understanding and awareness by enterprises of the full spectrum of impacts that may be due to their actions (Fauzi et al., 2019).

LCSA represents the highest and most complex level of sustainability assessment methods, encompassing all environmental, economic, and social aspects. This methodology encountered a growing interest and was continuously developed, with the aim of allowing a more holistic perspective regarding the impacts of processes, products, and systems. Thanks to the multidimensional evaluation of sustainability impacts, LCSA effectively supports stakeholders and decision-makers in making informed choices on sustainability (United Nations Environment Programme/Society of Environmental Toxicology and Chemistry, 2009). Despite LCSA being built upon the framework of ISO 14040:2006 (ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework), it is currently going through a phase of searching for the robustness of the methodology (Heijungs et al., 2013). There are no standardized procedures on how to conduct an LCSA, and this absence of univocity led to the employment of several different methods in conducting different LCSA studies (Paul et al., 2024). These diverging approaches to LCSA make it difficult to compare different LCSA studies and make results less reliable in the eyes of stakeholders. In addition, there is a lack of transparency in many publications concerning the discussion and description of their understanding of sustainability (Wulf et al., 2019). LCSA often requires a separate analysis of the environmental, economic, and social aspects of sustainability, involving the application and subsequent integration of three established and evolving methodologies: LCA, LCC, and s-LCA. (Costa et al., 2019). Therefore, several authors have attempted to then process the data collected from these three assessments, trying to obtain a single LCSA. This paper will present current techniques for conducting an LCSA based on the integration of three distinct analyses. To present the various LCSA approaches clearly and accessibly, the authors have grouped the analyzed papers into four categories: i) sequential analysis of LCA, LCC, s-LCA; ii) graphical representation approaches; iii) integration based on Multi-Criteria Decision Analysis (MCDA); and iv) tailored ranking methods and metrics.

This study aims to provide an accurate and accessible overview of the possible approaches for assessing a rigorous and integrated LCSA. This paper is structured as follows. Section 2 outlines the methods used to select the papers analyzed in this study, along with the criteria applied in the bibliometric analysis. This section also explains the basis for classifying the papers into four proposed categories. Section 3 presents the results of the bibliometric analysis with the review of the papers in each category. In Section 4, these results are discussed. Finally, some closing remarks and suggestions for future research.

2. Method

The authors conducted an overview of papers reporting LCSA analyses combining LCA, LCC, and s-LCA. In order to collect relevant articles, typical review protocols were put in place for the literature search (Ostojic, 2024)). With this regard, the following research query was used to scan the Scopus (Scopus) database: "Life Cycle Sustainability Assessment" OR "LCSA" AND "Life Cycle Assessment" OR "LCA" AND "Life Cycle Costing" OR "Life Cycle Cost" OR "LCC" AND "Social Life Cycle Assessment" OR "social LCA" OR "social-LCA" OR "s-LCA" OR "sLCA". The Scopus database was chosen because it indexes the most authoritative journals in this field. From the results obtained, papers up to 2024 were selected. Only journal publications were selected, including both articles and reviews. Review articles have been included because they reflect the degree of development and consolidation within each research field. This search selected 110 contributions, including articles and reviews, starting from a 2010 paper concerning the importance of clarity in the representation of results of LCSA (Finkbeiner et al., 2010). From this initial set, only 66 were judged as relevant to effectively analyze the approaches used for unifying the results of individual assessments (LCA, LCC, s-LCA) into an LCSA. In fact, case studies that did not complete the assessment with all three analyses and papers that presented conceptual issues regarding LCSAs but without naming or focusing on the actual methodologies for integrating the three aspects of sustainability were discarded. Similarly, papers that mentioned LSCA but focused only on one or two historical methods of analysis were discarded. Once the articles were selected they were subjected to a bibliometric analysis focusing on: i) the evaluation of the trend of scientific production over time; ii) the evaluation of the setting of paper (distinguishing among methodological framework or review or case study); iii) main affiliations of the corresponding authors by nation; iv) main journals for publication; v) main fields of applications (construction, energy, farming, etc.). The resulting 66 papers were carefully analyzed to explore the methodologies used to merge LCA, LCC, and s-LCA into LCSA. With an inductive approach, four different categories were identified to effectively group papers by homogeneity of the adopted integration approach: i) sequential analysis of LCA, LCC, s-LCA; ii) graphical representation approaches; iii) integration based on Multi-Criteria Decision Analysis (MCDA); and iv) tailored ranking methods and metrics.

3. Results

3.1 Bibliometric analysis

The most significant result of analyzing papers about LCSAs is the marked growth in the number of publications on this topic since 2016. This trend has remained consistent through 2024 as well (*Fig. 1*). Over time, a shift towards case study research is evident, with less focus on developing theoretical frameworks. (*Fig. 2*).

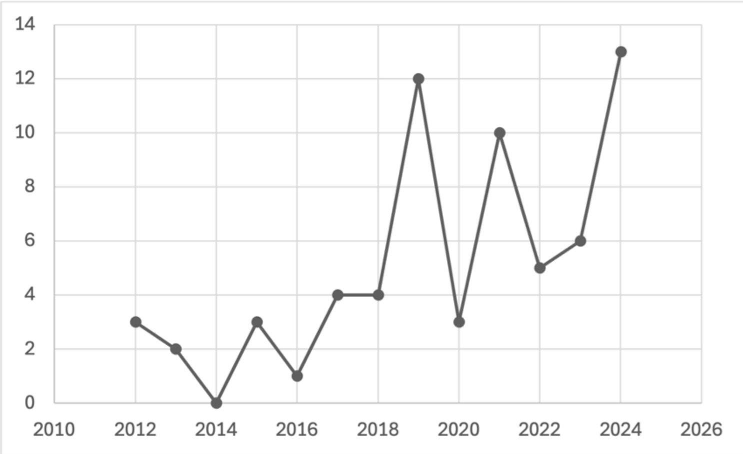

Figure 1: Number of papers over the years.

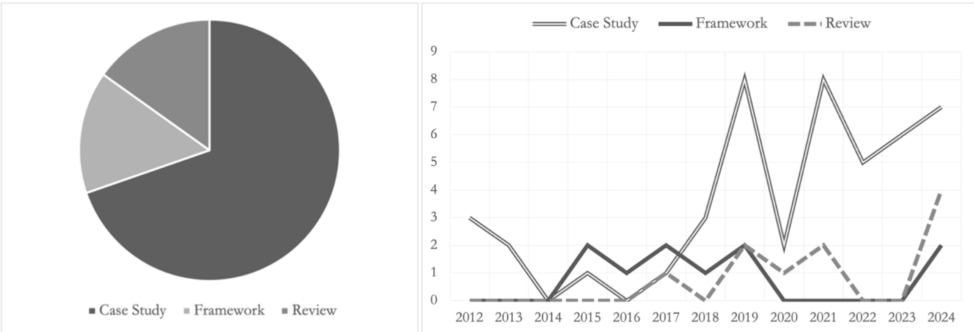

Figure 2: Type of paper: overall distribution (on the left), trend over time (on the right).

It is interesting to observe which nationalities are most representative in the development of papers on LCSAs that integrate the three different assessment instruments (LCA, LCC, sLCA). In *Fig. 3* it is possible to observe the distribution of papers by nation considering only nations with at least two papers that specify the nation in the principal affiliation of the corresponding author in at least two publications. Among the main fields of application, the construction sector emerges as the most widely applied domain for LCSA (*Fig., 4*). This field not only deals with the construction of new buildings but also with the renovation and energy assessments of pre-existing buildings, and is certainly a prolific sector, according to the criteria of this study (*Fig. 4, on the right*). Research in the construction industry is also flourishing as it seeks optimal solutions for reducing the environmental impact of buildings, and LCSAs can be a useful tool (Janjua et al., 2019). The proliferation of LCA and then LCSA models in the construction sector is also motivated by the social (high number of people employed), economic (important economic induced), and environmental (lots of raw materials and high emissions) impacts

(Backes et al., 2021b). The construction sector has been so prolific that there were enough studies to allow several reviews and analyses on the history of the evolution of LCSA. From the work of Marcinkowski and Haręża, for example, it is possible to observe tables with the methods of integration within the construction field (Marcinkowski, 2024). However, the different prolificacy of the fields of application does not affect the journal sectors where papers were published between 2012 and 2024. In fact, the most used journals are not sectoral journals, but journals that mainly deal with the topic of sustainability (*Fig. 4, on the left*).

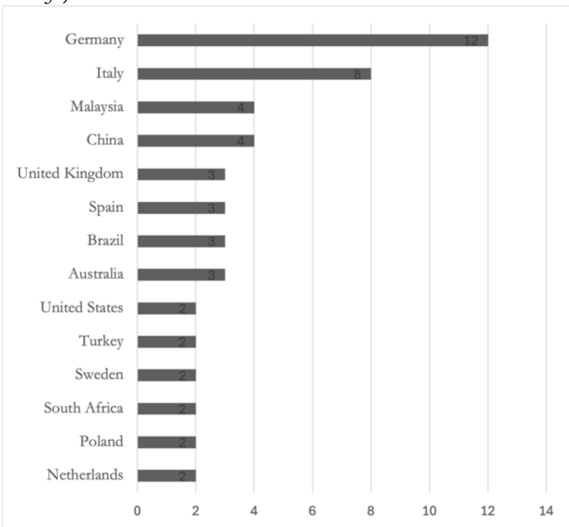

Figure 3: Principal affiliation of corresponding authors (at least two papers for country).

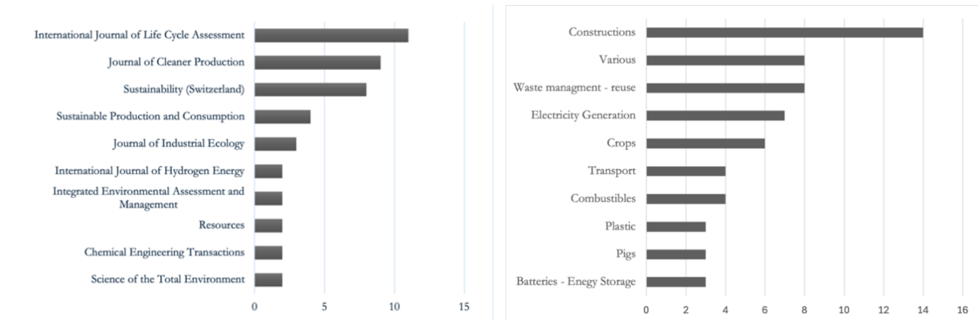

Figure 4: Principal journal for publication (on the left), principal field of application (on the right).

3.2 Analysis of the categories for LCSA

The section provides a review of the papers in each of the four identified LCSA integration categories.

3.2.1 Sequential analysis of LCA, LCC, s-LCA

The first category includes those studies that present a sequential analysis of LCA, LCC, s-LCA without a structured LCSA integration of methods and results. The LCSA, in these studies, therefore, results in the discussion of the three separate approaches. Indeed, a common method for the LCSA that has been used for years (and it is still used today) is the sequential analysis of LCA, LCC, and s-LCA. It consists in assessing the three different sustainability impacts (LCA, LCC, s-LCA) separately, and then discussing them in the same study as a unique process. The advantage of this methodology lies in the fact that, in attempting to aggregate the three different assessments into a single LCSA, it is necessary to apply normalization and weighting criteria. These two steps require different aspects of personal and potentially subjective evaluations, exposing the analysis to the risk of bias. Many authors decide to proceed with three different analyses, as Lizasoain-Arteaga et al. (2024), Mori et al. (2023), Popien et al. (2023), Gulcimen et al. (2023), Natthapong et al. (2023), Papo et al. (2022), Barrio et al. (2021), Gulcimen et al. (2021), Ferrari et al. (2019), Balasbaneh et al. (2018). While it is desirable to obtain results that are easily communicable to the public and the scientific community, the study by Wulf et al. (2017) states that with respect to the choice on the aggregation of the different assessments, it is nevertheless advisable to present the results without weighting or aggregation. In the study by Wulf, however, normalization and weighting were then carried out, but without the use of Multi-Criteria Decision Analysis or visual analysis (Wulf et al., 2017). Also opposed to the aggregation of results we find the work of Backes, that states that "no weighting of the individual pillars is allowed, nor can any of the pillars affect the performance of another pillar with its performance. The LCSA-results are independent of each other and can only be reported individually" (Backes et al., 2021a), (Backes et al., 2021b).

3.2.2 Graphical representation approaches

The second category encompasses studies where graphical communication is key to conveying LCSA results and integrating the individual LCAs, LCCs, and s-LCAs. Some authors have employed visual representations to ensure their results are easily comprehensible. In this type of study, the incorporation of images, graphs, and figures is not an addition to the text or an implementation of information, but rather a backbone of the study under consideration. Graphical representations can be of various types, such as schemes based on color density (the darker the color, the greater the impact (Zhang et al., 2024)). Widely used are radar patterns (Luthin et al., 2024a), (Luthin et al., 2024b), (Guarino et al., 2020), and spider diagram (Valente et al., 2020). Graphical representation often occurs after normalization is applied (also example with benchmark, radar, and Life Cycle Sustainability Triangle (LCST), a visual representation of the three pillars of sustainability: environmental, social, and economic (Savian et al., 2023)). We can also find in this category a score with questionnaires and triangle visualization (Omran et al., 2021). Also considered congenial to this category is the work of Dong et al. (2016), which performs an LCA, LCC and s-LCA separately, and then unifies the three of them in one aerogram. Among the relevant methods in this context is the Life Cycle Sustainability Dashboard (LCSD) (Schau et al. 2012, Traverso et al., 2012), a tool that uses a color scale to compare the results across the three dimensions of sustainability.

3.2.3 Integration based on Multi-Criteria Decision Analysis (MCDA)

The third category covers studies that use Multi-Criteria Decision Making (MCDM) methods to perform ranking, scoring, normalization and weighting of different impact assessments (LCC, LCA, s-LCA) to obtain the final LCSA results. Within this category, the individual assessments that compose LCSA are calculated independently, and MCDM tools are used to determine how to unify the individual outputs into a single result. Among the existing MCDM method, the adopted methods for LCSA are COMET (Gebrai et al., 2024), TOPSIS (Wang et al., 2019) and PROMETHEE (Balasbaneh et al., 2024). However, the most adopted MCDM method is AHP, used by Safarpour et al. (2022), Corona et al. (2019), Opher et al. (2019), De Luca et al. (2018), Xu et al. (2017), Dinh et al. (2020), Foolmaun et al. (2013). It was found also AHP-TOPSIS (Balasbaneh et al., 2021), AHP-ELECTRE (Liu S. et al., 2019), AHP-VIKTOR (Ren et al., 2015). Other studies apply MCDA in various ways, as Burchart et al., (2024), Furness et al. (2023). Some studies apply AHP e MAVT (Multi-Attribute Value Theory) (Nubi et al., 2022). Nieder-Heitmann et al. (2019) apply MAUT (Multi-Attribute Utility Theory). More MCDM are used (Zheng et al., 2019), and Fuzzy techniques are used by Kouloumpis et al. (2018). There is a LCSA with MCDA in combination with stakeholder profiles (Ekener et al., 2018). De Luca et al. (2015) employed the AHP MCDM to legitimize the executed s-LCA and make it integrable with the LCA and LCC in an LCSA. Other examples are Berticelli et al. (2024) and Visentin et al. (2022). Other MCDA are carried out by De Luca et al. (2017) and Vinyes et al. (2013). Some reviews focused on MCDA are those of Holden et al. (2024), Ostojic et al. (2024) and Alejandrino et al. (2021), a paper where they present a review which includes MADM (Multi-Attribute Decision Making), MODM (Multi-Objective Decision Making) and DEA (Data Envelopment Analysis). Other interesting studies include those of Liu K.F.R. et al. (2019), that regards SEA of Taiwan, with use of AHP and LCSA, and a Multicriteria prioritization framework by Grubert (2017).

3.2.4 Tailored ranking methods and metrics

Some studies propose approaches for integration that do not fall in the previous categories. They focus primarily on creating indicators that could be reported easily. The methods in this category often respond to specific needs of the studies under investigation and construct procedures tailored to certain needs of the authors. The work of Visentin et al., (2024) belong to this category. Chen et al. (2023) focus on Relative Sustainability Index (IRS). Amini Toosi et al. (2022) propose an index also applied synergistically with Machine Learning techniques. Other indicators were proposed by Masilela et al. (2021), Tsambe et al. (2021) and Zira et al. (2021), with a Relative Sustainability Points (RSP). Hoque et al. (2019) propose a survey-based framework. Manzardo et al. (2012) modified Grey Relational Analysis (S. Liu et al., 2022) to address the issue of uncertainty in LCSA. Worth mentioning is the work by Neugebauer et al. (2015), who apply a tiered approach, a hierarchical strategy that elaborates the LCSA by going through three levels of computation of increasing complexity.

4. Discussion and conclusions

The LCSA methodology allows a holistic vision of environmental, social, and economic impacts. Nevertheless, this method is still underdeveloped, it is not equally adopted among different sectors, and it presents some challenges. The present study aims to provide an organized and easily accessible overview of the various approaches to LCSAs, focusing on the integration of its components. In recent years, many resources have been dedicated to addressing the complex integration of LCA, LCC, and s-LCA into a single LCSA through case study applications. Despite this effort, no single methodology has been definitively established to date, although the use of techniques pertaining to MCDM is increasingly established. The proposed bibliometric analysis suggests a growing area of research, with distinct application possibilities also in the industrial and construction fields. Although the construction sector currently appears to be the primary field of application for LCSAs, this methodology is suitable for a wide range of industries. The predominance of studies in construction can be attributed to the sector's significant economic, social, and environmental impacts, already well-documented through the long-standing use of LCA in the industry, as noted by Barbhuiya et al. (2023), rather than to any intrinsic limitation of LCSA in adapting to other contexts. The flexibility of the application of LCSA methodologies allows for a range of different areas, however, immaturities in integration systems are still present. Over the years, there has been a decreasing focus on merely theorical works and the construction of theoretical frameworks has been enveloped in papers concerning both advances in theoretical approaches and application on case studies.

Although combining data from individual LCAs, LCCs, and s-LCAs into a single LCSA is not always considered necessary in the studies analyzed, it is still crucial to communicate research results in a clear and understandable way for both stakeholders and the research community, as stated from the early studies in this sector (Finkbeiner et al., 2010). The category of methodologies for integrating various assessments would seem to be MCDAs, as they are flexible but sufficiently reliable. These techniques can also be applied for both the construction of rankings and indicators and to facilitate the subsequent visual representation.

Although the landscape of publications over the past 15 years presents a good number of reviews, these are often directed toward analyzing issues such as the current state of art of LCSA (Costa et al., 2019), the development of LCSA in case studies (Alejandrino et al., 2021), or the application of LCSA on specific argument (Milić et al., 2024), or perhaps proposing new areas of application for life cycle thinking (Petit-Boix et al., 2017). Instead, this study focuses not only on the evolution of different integration methodologies but also on their archiving and categorization, intending to allow new studies in this field with an additional tool for understanding these different analyses. The used and proposed categorization involved in this paper can facilitate navigation through existing information on data integration within the LCSA framework. However, the categories into which the various studies were classified do not represent rigid domains, as the various articles presented can sometimes be considered to consist of more than a single aspect. In fact, categorization was done on the basis of the prevailing peculiarity of the method under consideration.

Focusing on the integration of all three components of LCSA provides a clearer understanding of how previous studies have approached comprehensive sustainability assessments. This holistic perspective highlights the challenges and methodologies involved in achieving full integration. However, it may also result in the exclusion of studies that focus on partial (two-component) integrations and potentially relevant techniques. Future research could therefore broaden the scope to include two-component integrations, to capture a wider range of integration approaches. In order to enable adequate comparison between different application domains and between studies within the same domain, as well as to proceed with the creation and drafting of increasingly accurate guidelines, it will be essential to develop robust frameworks that systematically integrate the three dimensions of sustainability - environmental, social, and economic - within a coherent LCSA methodology. In particular, integrating MCDA tools within LCSA appears to be a promising area of research that supports more transparent and stakeholder-oriented decision-making. Future studies should explore how different MCDA methods can be tailored and embedded in LCSA to prioritize trade-offs and value-based judgments, paying attention to the possible introduction of subjectivity or bias factors. Another possible development for MCDA studies could be the comparison of MCDA tools and how to apply them to reduce green washing phenomena through the inclusion of stakeholders. Future studies should also consider the involvement of stakeholders in the methodological design of LCSA tools, in order to explore how participatory processes can strengthen the role of these tools in sustainability governance. Future studies should also clarify how such involvement may lead to more robust, socially accepted LCSA applications that better connect product-level data with policy-level decision-making needs. It will be important to verify that the adaptability of LCSA methods under development is maintained across all potential areas of application, from construction to agriculture. To allow better growth of knowledge in this area, it will also be necessary to find strategies for structuring and disseminating LCSA methodologies that are accessible and understandable to everyone in the field, from researchers to managers and stakeholders. With this regard, efforts should be made to bridge micro-level (product-specific) assessments with macro-level (policy or sectoral) sustainability evaluations, as well as to explore how to make LCSA more adaptable to stakeholder needs and contexts, including through participatory methods for setting boundaries, weights, and sustainability targets.

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