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ENVIRONMENTAL LCC

Integrating life cycle assessment and life cycle cost: a review of environmental-economic studies

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Abstract

Purpose The purpose of this document is to carry out a critical review of the existing literature by specifically addressing the following: (i) the integration of life cycle assessment and life cycle cost assessment from the perspective of research topics, category and scope of study, authors, institutions, countries, and journals working on or publishing related studies, and (ii) the main aids, challenges, opportunities, methodological difficulties, and current research efforts on the integrated approach of both tools.
Methods A systematic review was conducted to identify studies with an integrated use of life cycle assessment and life cycle cost in several areas. An analysis of the main aspects of the studies identified, such as bibliographic reference, year of publication, institution where the research was conducted, country, area of application, category of study, journal of publication, impact factor, and number of citations was conducted. After a search in the Science Direct, Scopus, and Web of Science databases, 349 documents were identified. After a series of filters (excluding gray literature, reading titles and keywords, reading abstracts, and reading full-texts), which helped ruling out articles that did not contribute to investigating the integration of life cycle assessment and life cycle cost assessment, 90 documents were selected for a detailed analysis.
Results and discussion The leading role of the USA and European countries in this issue should be highlighted. The integration of life cycle assessment and life cycle cost seems to be most advanced in the areas of building design and civil construction. Different strategies for the integration of the methodologies are also found, being mathematical modelling and programming for optimization, and multi-criteria decision-making the most recurrent methods. Moreover, there seems to be more challenges than opportunities in said integration. The challenges include the monetization of environmental impacts, higher volatility of economic data compared to environmental data, and differences in environmental and economic background data. These challenges can be turned into opportunities in the development of more comprehensive methodological approaches.
Conclusion Challenges (e.g., time-, resource- and knowledge-intensive, different scopes) and opportunities (e.g., common system boundaries, benefitting from LCA structure to conduct LCC) for the integration of life cycle assessment and life cycle cost were identified. This combined approach allows projects, products, and services to reduce environmental and economic impacts, which can be quantified and compared through improved assessment of potential trade-offs.

Keywords Life cycle assessment · Life cycle cost · Trade-off · Environmental impact · Economic analysis · Eco-efficiency · Sustainability · Review

1 Introduction

In recent years, organizations from a wide range of sectors have sought to differentiate themselves through a competitive advantage that aligns not only techno-economic but also environmental aspects (Palomares-Rodríguez et al. 2018). Among the objectives of the organizations, the optimization of processes, cost reduction, and minimization of environmental impacts are in the strategic core, so that competitiveness and sustainability are objectives of equal importance. Therefore, assessing the dimensions of sustainability can help develop policies, and they become strategic factors in the decision-making process (de Souza et al. 2019). Based on that, life cycle assessment (LCA) and life cycle cost (LCC) provide consistent information on the

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environmental and economic dimensions of sustainability, as they can serve as a basis for the adoption of economically feasible and environmentally sound strategies (Rashidi et al. 2018). Both tools (as they are referred to hereafter and for the remaining of this manuscript), LCA and LCC, emerged in the mid-1970s from the energy crisis, each with a different focus, in which LCA accounts for energy and material consumption and emissions from mass and energy balances while LCC reports on the economic aspects of all stages of the process (Steen 2005).

LCA has developed since then (at different rates over the decades) until today. LCA has now evolved to report on the global environmental impacts associated with the process under study, considering from raw material extraction to final disposal (Guinée and Lindeijer 2002). LCA is carried out in four phases according to ISO 14040 and ISO 14044: (i) goal and scope definition, (ii) life cycle inventory analysis (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation (ISO 2006a, 2006b). Standards continue to provide an objective structure to ensure reliable and comparable results (Martins et al. 2018). Furthermore, according to Barros et al. (2020a) and Araújo et al. (2019), LCA is the most comprehensive tool for assessing the environmental profiles of goods and services. Therefore, the decision-maker can reduce the environmental impact when proposing improvement actions in those stages of the process that account for the highest shares of impacts in the environmental profile. This tool not only makes it possible to determine the environmental consequences associated with greater efficiency in processes, services, and products (González-García et al. 2014), but can also guide the adoption of more sustainable processes and lifestyles (Severis et al. 2019).

The basis of the LCC methodology was established in the 1970s as a method for calculating the total life cycle costs of products (Brown 1979) and as information in strategic business and policy decision-making (UNEP/SETAC 2009). There are even previous references to the use of this tool in the purchase and use of military equipment by the US Department of Defense in the 1960s (Jolliet et al. 2015). Unlike LCA, LCC does not have a general standard that provides guidelines for its use/application. One of its most commonly used guidelines is found in ISO 15686-5 (ISO 2017), which aims at planning the life of buildings and built assets. As stated in its definition, LCC aims not only to calculate the costs of acquiring raw materials, but also the costs of operation, maintenance, and final disposal (Hunkeler et al. 2008); thus, decision makers can act to improve the economic indicators of the system's life cycle (Fallah et al. 2013). LCC studies can also include the costs of externalities, i.e., the costs of environmental impacts caused by the system or product (Steen 2005), motivated by the "polluter pays" principle. Currently, there is a growing importance of LCC in some areas of public administration, mainly in public procurement (Hochschorner and Finnveden 2006; Sterner 2002; von Deimling et al. 2016).

Given the relevance of both tools, an apparent weakness for companies to use LCA is the understanding of what the results mean for their economic indicators (Steen 2005). In that sense, an integration of LCA and LCC seems beneficial. While LCA requires an extensive data set from mass and energy balances identified in the life cycle inventory (LCI) phase, LCC requires monetary information in terms of financial resources (expenditures and revenues).

Based on the aforementioned, studies have been identified that address environmental and economic aspects using LCA and LCC (De Menna et al. 2018; Early et al. 2009; Ilg et al. 2017; Márquez et al. 2008). Along with the integration of these tools, trade-offs between the environmental and economic approaches have been reported in the literature (Ameli et al. 2017; Lee and Thomas 2017; Lidicker et al. 2012; Norris 2001; Pretel et al. 2015; Umer et al. 2017; Van Kempen et al. 2017). The simultaneous application of LCA and LCC may make it easier to identify environmental and economic trade-offs. With a life cycle thinking underlying the applications of both LCA and LCC, it might make it more interesting for decision makers to take actions and make decisions based on values or normative frameworks. Schmidt (2003) comments that among the various design and process characteristics, a great challenge is to combine the environmental and the economic dimensions, obtaining a feasible solution for both.

In published research, LCA and LCC are often used in parallel or with little integration, and there does not seem to be a mature theoretical approach to their integration (Bierer et al. 2015). There is a gap in the related literature regarding the main issues in environmental-economic assessment by using LCA and LCC; neither have the existing studies identified the main researchers and institutions working on this combined approach worldwide. The joint use of these tools is justified to seek environmental-economic efficiency in production systems, and to minimize the trade-offs between environmental and economic impacts. Therefore, this paper aims to conduct a critical review of the existing literature by specifically addressing: (i) the integration of life cycle assessment and life cycle cost assessment from the perspective of research topics, category and scope of study, authors, institutions, countries and journals working on or publishing related studies, and (ii) the main aids, challenges, opportunities, methodological difficulties, and current research efforts on the integrated approach of both tools. This analysis aims to provide a theoretical basis and insight into the main issues on the combined approach via the systematic review of the existing literature on the topic.

2 Methodology

2.1 Selection of documents

All methodological procedures for the selection of documents were organized in stages, and the most relevant studies were identified using an adaptation of the Methodi Ordinatio (Pagani et al. 2015). All related existing literature until 27 April 2020 was retrieved from the Web of Science (WoS), Science Direct (SD), and Scopus databases. The search was intended to gather research and review articles, available in English. The EndNote software tool was used for reference management. Figure 1 shows the steps followed to perform the review.

1. Database search: the searches in the Science Direct, Scopus, and Web of Science databases were conducted in April 2020, and 349 documents were compiled, including all types of documents, such as research and review articles, book chapters, and conference proceedings.
2. Removing duplicates and gray literature: all duplicate papers and gray literature (papers that are not peer-reviewed source articles) were excluded. Only research and review articles (both published and in press) from peer-reviewed journals were considered. This is due to the superior scrutiny and rigour with which such research is examined prior to publication, providing a reliable mechanism for quality control (Catuogno et al. 2016). In addition, perspective/position papers, book chapters, books, and conference proceedings are not always subject to peer review (Manca and Ranieri 2013; Marceau et al. 2019). Furthermore, it should be noted that conference documents contribute little to literature reviews, given the limited information included in this type of document as well as the additional time and complexity involved in including them in the analyses (Butler and Visser 2006; Xu et al. 2018).
3. Screening title and keywords: all titles and keywords in each paper were read and all papers that did not provide substantial contribution to understanding the integration of LCA and LCC were ruled out.
4. Screening abstracts: as in the previous filter, all abstracts were read and articles that did not contribute to understanding the integration of LCA and LCC were excluded.
5. *InOrdinatio* coefficient: at this step, the Methodi Ordinatio suggests calculating the *InOrdinatio* coefficient (Pagani et al. 2015). The method ponders the relevance of the studies taking into consideration their publication year, number of citations, and impact factor. The number of citations of each document were found using Google Scholar on September 30, 2020, and the impact factor (IF) was found using Journal Citation Reports (JCR) (2019). The *InOrdinatio* coefficient can be seen in Table 2 (Appendix).
6. Full-reading: after the first screening, 90 articles were selected and constituted the final portfolio, which was compiled in a spreadsheet for analysis. The analysis of the articles included their characteristics, the LCA and LCC results reported, and the integrated use of the methods.

The keyword co-occurrence map (see Fig. 2) was built using the VOSViewer software tool, using all 90 documents, given the following settings: map based on: text data; fields: title and abstract; counting method: full count; minimum number of occurrences of a term: 5; number of terms selected: total number of keywords; display: all keywords. The Microsoft Power BI (Business Intelligence) desktop was used to build the graphs in the paper (see Figs. 3 and 4) to allow clearer interpretation.

2.2 Characteristics of the articles

The articles found (90 documents) were analyzed in terms of (i) bibliographical reference, (ii) year of publication, (iii) institution where the research was conducted, (iv) country, (v) area of application, (vi) category of study, (vii) journal of publication, (viii) IF, and (ix) number of citations. The characteristics of the articles are detailed in

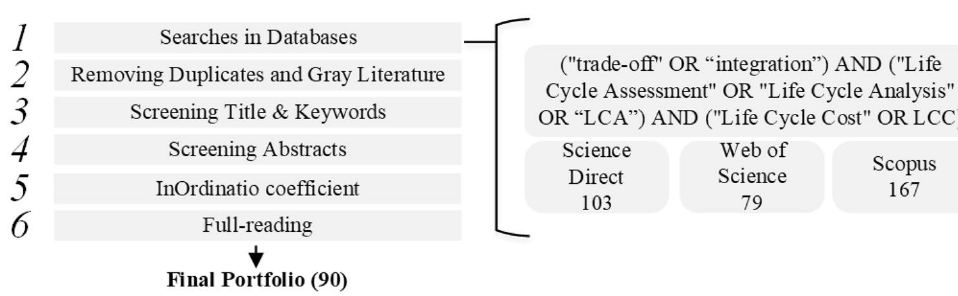

Fig. 1 Steps to conduct the literature review

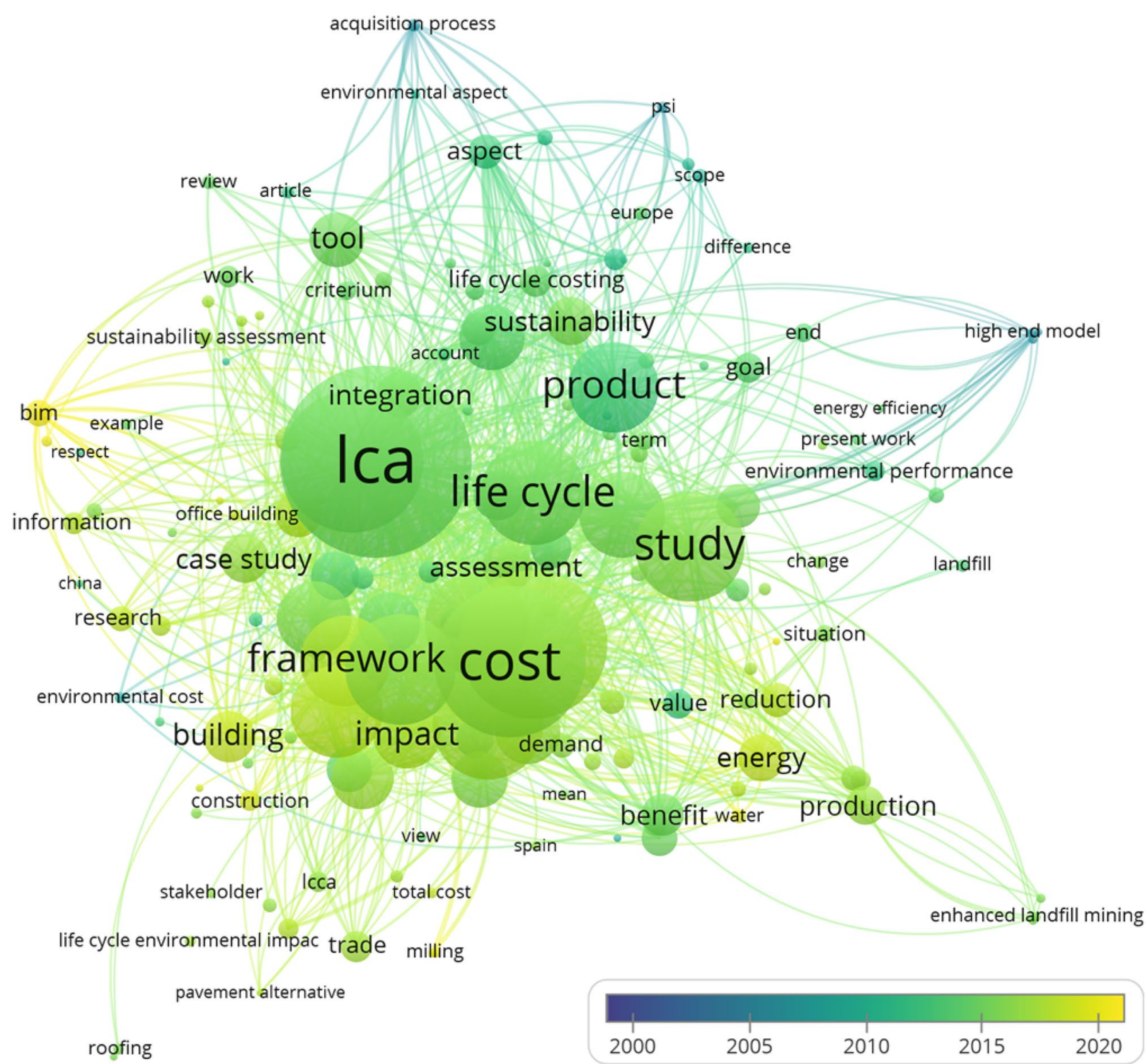

Fig. 2 Co-occurrence of terms in the studies from the final portfolio

Table 2 (Appendix). The institution and the country were retrieved considering the first author of each document. The documents were classified according to different sectors: Energy, Waste Management, Health, Construction, Industrial, Academic, Agriculture, Rainwater Harvesting, and Logistics. The categories of study were divided into case study, proposal of tool/methodology/framework, and review. The IF was retrieved from the journal citation reports (JCR). Finally, the number of citations was retrieved from Google Scholar on September 30, 2020.

2.3 Integrated use of LCA and LCC

Data was collected on the methods used to integrate LCA and LCC, which allowed verifying how these methods allowed the integration or assessment of the trade-offs between those. Other criteria were also observed, such as the discussion of the trade-offs between economic and environmental approaches, the use of methods and concepts complementary to integration, for example, multi-objective linear programming, eco-efficiency, fuzzy logic, and analytic hierarchy process (AHP).

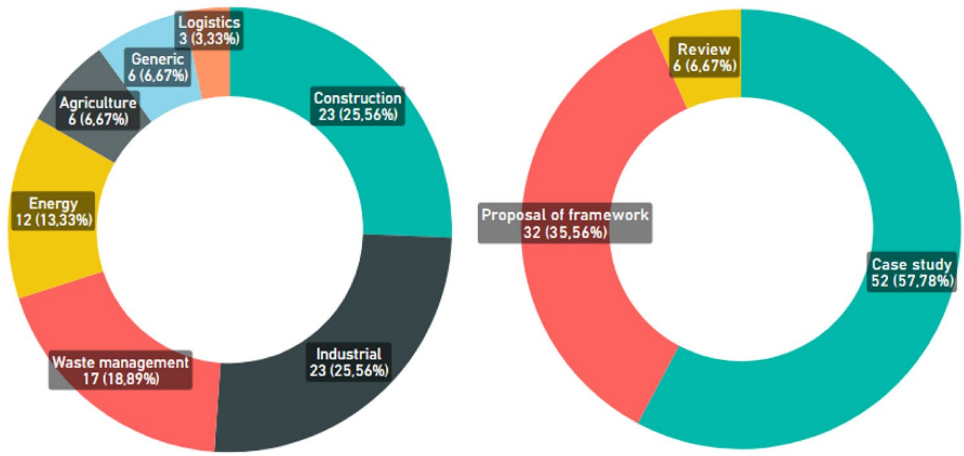

Fig. 3 Category of study and area of application

3 Analysis of the main topics and sectors combining the LCA-LCC approach

3.1 Characteristics of the studies in the existing literature

From the research topics addressed in the existing literature, several issues of integration and trade-offs between LCA and LCC were observed. As it can be seen in Fig. 2, the most common themes addressed were LCA (122 occurrences) and cost (97 occurrences). Some topics seemed scattered (both over time and expressed with different terms/names), with low frequencies that probably mean non-standardized use of terms for indexing. An example of this is the various terminologies found for life cycle cost, which may include life cycle cost (42 occurrences), life cycle cost analysis (9), LCCA (13), LCC analysis (7), and life cycle costing (20). In addition, the early approaches that sought to integrate LCA and LCC did not seem to follow a pattern. However, in recent years the relevance of LCA and LCC in simulating the costs and environmental impacts (mainly related

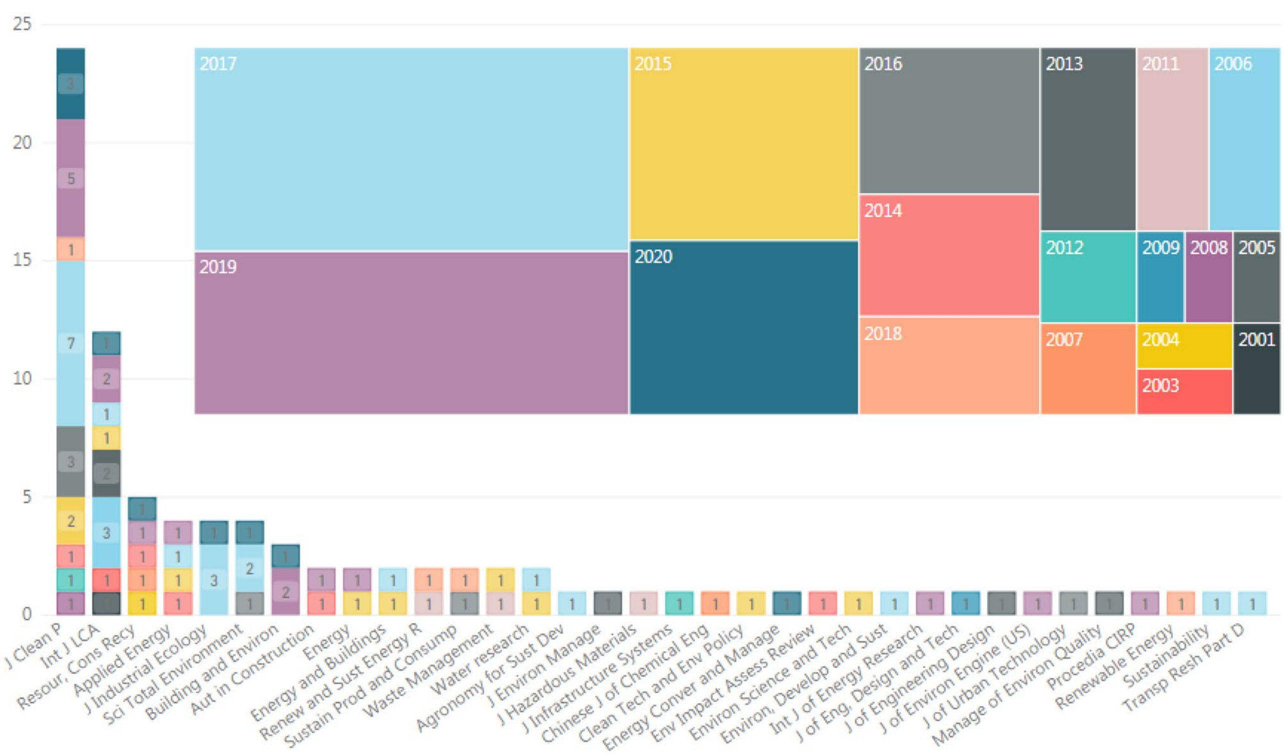

Fig. 4 Number of publications per journal and per year

to energy consumption) of buildings at the design stage are highlighted.

It can be noted from Fig. 2 that, although LCA and LCC had emerged decades earlier, up until 2000 no research efforts had been registered in the search to couple these two tools in environmental-economic analyses. Moreover, this movement of integrating environmental and economic aspects by using LCA and LCC seems to have been latent but shy between 2000 and 2010, and it was only boosted in the last decade. On top of it receiving much more attention, especially in the second half of the last decade, the efforts to couple LCA and LCC seem to have broadened the scope of this research theme. While early research (2000–2010) devoted efforts to providing an assessment of different alternatives of products, and seemed to be slightly skewed towards a more environment-driven approach, the efforts made in the last few years seem to have focused on broadening the set of criteria included in the environmental-economic assessment, investigated the environmental and economic implications of a range of sectors (where the civil construction stands out), and have also sought a greater balance between environmental and economic aspects in more sustainability-driven assessments.

Three different categories of study were identified, namely, case study, proposal of tool/methodology/framework, and review. Case studies are articles that feature the use of methodologies, with benefits or outcomes for the organizations or their stakeholders. The proposal of methodology is the proposal of a technique or method that may be specific to the authors or derived from previous research. Some studies propose a methodology and apply it to a case study. In cases where more than one category could be observed, the predominant category was adopted for the analysis.

The articles in the final portfolio showed a predominance of case studies, as shown in Fig. 3. Several of the 52 articles in the final portfolio were case studies. The category of proposal of tool/methodology/framework comprised 32 articles, and the reviews represented 6 documents in the final portfolio. Furthermore, seven different areas of application were identified for the final portfolio, such as construction (23), industry (23), waste management (17), energy (12), agriculture (6), generic (6), and logistics (3). This information can be seen in Fig. 3 and in Table 2 (Appendix).

The construction sector has been the subject of the largest number of studies (Santos et al. 2020a, 2020b; Basbagill et al. 2014; Best et al. 2015; Islam et al. 2015; Zhang et al. 2020a; Lidicker et al. 2012; Petit-Boix et al. 2017a; Conci et al. 2019; Wang and Zimmerman 2015; Zhang 2017; Hong et al. 2019). The researchers with the highest number of publications on this topic were Simões, C. L. (Simões et al. 2013a, 2013b, 2016), Azapagic, A. (Santoyo-Castelazo and Azapagic 2014; Kouloumpis and Azapagic 2018; Aberilla et al. 2020), and Santos, R. (Santos et al. 2019, 2020a, 2020b).

The two most recurrent journals in the list of 34 were the Journal of Cleaner Production (J Clean Prod) and The International Journal of Life Cycle Assessment (Int J Life Cycle Ass), with 24 and 12 papers, respectively, based on the final portfolio. Figure 4 shows the number of publications per journal and year. As it can be observed, the first study addressing the combined use of LCA and LCC, mentioning trade-offs, appears to have been published in 2001 by Norris (2001). However, the largest number of publications has accumulated in recent years. The year 2017 was the most representative in terms of the number of publications, reaching 21 documents in 2017, and 16 documents in 2019. In addition, Fig. 4 presents an infographic (following the color legend) of the number of studies per journal and year.

In addition, as far as institutions are concerned, a total of 77 institutions were found (see Table 2, Appendix). The universities with the largest number of publications were the University of Manchester (UK) (Santoyo-Castelazo and Azapagic 2014; Kouloumpis and Azapagic 2018; Aberilla et al. 2020), the University of Minho (Portugal) (Simões et al. 2013a, 2016), Stanford University (USA) (Basbagill et al. 2014; Best et al. 2015; Grubert 2017), and Vrije University Brussels (Belgium) (Santos et al. 2019, 2020a, 2020b), with three publications each. A large disparity in the number of studies (considering the country of affiliation of the first author in each study) per country was noted, with the United States (US) being the country where most studies were observed. The US accounted for 17 studies, followed by Spain (10), Belgium (7), Portugal (7), China (6), Germany (6), and the United Kingdom (UK) (5).

Further information on the final portfolio, such as the IF of the journals, and the number of citations are reported in Table 2 (Appendix). The IF starts from zero and goes up to 10.556 (Renewable and Sustainable Energy Reviews) (Harris et al. 2018). The number of citations starts from zero (recently published articles, around 2020), and reaches 424 citations (Norris 2001).

3.2 LCA characteristics

The study sought to identify aspects of LCA studies that can be seen through a range of different studies in different fields, which can be used to point out ways to integrate LCA and LCC, such as the use of standard procedures, software tools, impact categories, and methodologies for impact assessment. The first outcome relating to LCA was an analysis that considered whether the studies had the same structure as the international ISO standards (2006a, 2006b). In this sense, more than 60% of the studies mentioned are based on ISO standards (2006a, 2006b), as guidelines for the description of LCA. However, the other 40% of the studies that did not mention having followed the two ISOs are still relevant in the scientific field and consider life cycle thinking. To Heijungs (2014), correctly communicating a life cycle assessment is essential for advances, updates, and the gathering of new researchers in the field.

Other analyses considered the use of computer tools to calculate life cycle impacts, based on data inventories. In addition, many studies did not use software tools or did not mention their names. However, two software tools were used more extensively in the studies, namely SimaPro and GaBi. According to Barros et al. (2020b) most LCA studies use the SimaPro software tool, being the most common worldwide, to calculate life cycle impacts.

It was noted that many studies considered the climate change impact category in the assessment. Of the studies that conducted LCA, at least 70% performed analyses on climate change. Other important impact categories used were acidification, eutrophication, human toxicity, and ozone depletion. Environmental impacts are related to a common unit and are summarized in environmental effects (such as climate change, acidification and others) or aggregated into an environmental index (Fallahpour et al. 2012).

In terms of the LCIA methods used, different methods were found. Some articles used three or more methods at the same time (Lee and Thomas 2017; Arceo et al. 2019; Calado et al. 2019). Ercan et al. (2015), in particular, used a hybrid LCA method, without the use of a clear LCA methodology. The most widely used methods were the IPCC and ReCiPe, followed by the CML, and Eco-Indicator 99. Furthermore, the analysis did not consider the different versions of the software tools used, nor the period covered by the methodology, such as 20 or 100 years of impact. Islam et al. (2015) used their own method, developed in Australia, called the Australian Impact Method. Similar to the analyses of LCA characteristics, LCC characteristics were also observed in the final portfolio studies, as discussed in the following section.

3.3 LCC characteristics

LCC does not have a general standard to guide its use. However, there are some guidelines that should be consulted when using this method (see, for example, Hunkeler et al. 2008), mainly for buildings and constructed assets—ISO 15686–5 (ISO 2017). According to Hunkeler et al. (2008), there are three types of LCC: conventional LCC, environmental LCC, and social LCC.

In the final portfolio of studies, different methods were identified. There seems to be a common agreement to use capital expenditure (CAPEX) and operating expenditure (OPEX) as a way to express the results when an LCC study is conducted. However, there does not yet appear to be a common agreement on how to compile the data, or how to deal with uncertainties in the calculation of the sum of the costs for different time frames.

There is no global standard to guide the organization of an LCC study. However, it can be observed that most of the investigations in the final portfolio of this study express LCC results as the sum of the costs per functional unit, as in a LCA, where a functional unit is chosen to be used as a parameter. The difference between the studies lies mainly in the choice of what will be accounted for in the sum of the costs, and this depends on the objective of each study.

In that sense, an important issue is that of the purpose of LCA use. As observed in the case of LCA, most manuscripts using LCC aim to compare products, processes or projects, using economic aspects to indicate the one that stands out according to specific environmental-economic aspects in each study. Differences in cost categories, such as direct and indirect costs, internal and external costs, operational and non-operational costs, differ among the different studies in the final portfolio.

External costs can also be accounted for in an LCC, such as the costs of prevention or damage to the environment and society, which are usually calculated by monetizing impacts. However, monetization is not always the only way to integrate LCA and LCC. There have been examples of studies that use fuzzy logic based on linguistic variables to establish a common ground between environmental and economic issues (Kouloumpis and Azapagic 2018). Another feature is accounting for the change in the value of money over time, which is another economic concept, applied to future and foreseeable costs.

4 Synthetic overview on the integration of LCA and LCC

4.1 Aids for LCA-LCC integration

The current research efforts to integrate LCA and LCC are evidenced in the growing interest in the integration of the two tools, as it can be seen in the final portfolio (90 documents). It could be observed that LCA and LCC were often used together along with a range of other methodological aids, e.g., cost–benefit analysis (e.g., Jeswani et al. 2010), environmental impact assessment (e.g., Fallahpour et al. 2012), and system disruption analysis (e.g., Buytaert et al. 2011). On other occasions, LCA and LCC were integrated in the search for the determination of the eco-efficiency of a system or product (Best et al. 2015; Braulio-Gonzalo and Bovea 2017; Lorenzo-Toja et al. 2016; Mami et al. 2017; Petit-Boix et al. 2017a). In addition, other tools were also used jointly with the LCA-LCC approaches, such as a multi-criteria approach to account for both environmental and economic impacts, to address uncertainties and to standardize data. Table 1 presents the most frequent methodological aids observed in the studies.

The use of the aids presented in Table 1 directly influences the success of the integration and/or the evaluation of the trade-offs between LCA and LCC. Since there is no standardization on how to integrate LCA and LCC, the use of auxiliary tools that address multiple criteria and the uncertainties and sensitivity of the variables is of great importance when dealing with such complex tools.

A widely used technique is multi-criteria decision analysis (MCDA). Zanghelini et al. (2018) present a review on MCDA methods in LCA studies, and these include mathematical modeling, analytic hierarchical process (AHP), fuzzy logic approach, among others. These methods have been used in various systems and different intents: the automotive industry (Ameli et al. 2017), building design (Basbagill et al. 2014), energy efficiency (Nguyen et al. 2017; Wu et al. 2017), and eco-efficiency measures (Zhao et al. 2011), in order to reduce environmental and/or economic impacts.

In addition, it is possible to observe the extensive use of graphics and mathematical models to integrate the outcomes from both approaches. The use of two-dimensional graphs made it possible to detect the relationship between economic and environmental impacts. Some examples of these graphs can be seen in the studies of Escobar et al. (2015) and Mami et al. (2017). The use of the Pareto chart was also observed, as it can be seen in the study of Zhao et al. (2016). The use of MCDA was more present in studies that used mathematical models to consider both environmental and economic impacts. Sensitivity analysis can also be mentioned, in order to observe the behavior of a variable given changes in the system parameters, as it allows determining the robustness of variables within a system. Nonetheless, traditional LCA sensitivity analysis could be misleading for decision-making, as it generally does not consider the possibility of improving specific parameters (Yao and Huang 2019).

The use of these aids was essential to assess the trade-offs between LCA and LCC results. In summary, several tools have been used to assist environmental and economic assessment; these include life cost–benefit analysis, eco-efficiency, and LCC (Jeswani et al. 2010). Nonetheless, their integration into a common methodological framework is still scarce (Kouloumpis and Azapagic 2018).

4.2 The emergence of LCA-LCC integration frameworks

It seems that frameworks have emerged that seek to propose the integration of LCA and LCC, mainly in recent years. LCC has been used as an approach to calculating costs and making comparisons from a product perspective, rather than from a life cycle perspective (Fauzi et al. 2019). Many times, the use of LCA does not seem sufficient for profit-directed organizations to make a final decision relying only on environmental assessment results (Deng et al. 2016), hence, the joint use of LCA and LCC supported by tools capable of providing sound results on the environmental and economic aspects of sustainability may be used.

Life cycle thinking needs to be taken into account in life cycle assessments, be it in the environmental (LCA), economic

Table 1 Methodological aids most frequently used along with LCA and LCC

Aid	Description	References
Multi-criteria decision analysis	Analysis with various terminologies and application modes used to concentrate multiple values of different criteria into a single factor	De Luca et al. (2017), Grubert (2017), Santos et al. (2017), Santoyo-Castelazo and Azapagic (2014), Umer et al. (2017), Zanghelini et al. (2018), Akhtar et al. (2015), Dong et al. (2014), Eddy et al. (2013), Hong et al. (2019), Miah et al. (2017), Nieder-Heitmann et al. (2019), Ribeiro et al. (2008), Schmidt (2006)
Life cycle sustainability assessment	This assessment seeks to integrate LCA, LCC, and social life cycle assessment	De Luca et al. (2017), Nguyen et al. (2017), Petit-Boix et al. (2017b), Santoyo-Castelazo and Azapagic (2014), Van Kempen et al. (2017), Aberilla et al. (2020)
Pareto principle	It is a concept based on the assumption that most effects are due to a minority of causes. However, it can be applied in several ways; as a Pareto chart, when one considers, for example, that the top 20% of impacts represent 80% of inputs	Ercan et al. (2015), Islam et al. (2015), Santos et al. (2017), Wu et al. (2017), Zhao et al. (2016), Conci et al. (2019), Gonzalez et al. (2018)
Mathematical programming	Use of mathematical and computational models to achieve an objective function, respecting restrictions imposed by the system	Ameli et al. (2017), Best et al. (2015), Ercan et al. (2015), Huang et al. (2017), Lidicker et al. (2012), Santos et al. (2017), Wu et al. (2017), Zhao et al. (2016), Budzinski et al. (2019), Calado et al. (2019), Tulus et al. (2019), Yao and Huang (2019), Zhang et al. (2020b)

(LCC), social (social life cycle assessment (SLCA)), and also sustainability (life cycle sustainability assessment (LCSA)) aspects. In the studies of Selech et al. (2014) and Witczak et al. (2014), life cycle thinking was evaluated in economic and environmental aspects, respectively, in small and medium companies.

A set of frameworks has been presented in a wide range of manuscripts (Abou-Hamad and Abu-Hamd 2019; Arceo et al. 2019; Fregonara et al. 2016; Santos et al. 2019; Tulus et al. 2019; Umer et al. 2017; Yao and Huang 2019) which provide detailed guidance on how to link environmental and economic analysis. It appears that frameworks have been preferred to other approaches (such as models), as they are more generic and have greater potential for transferability. Frameworks often provide guidance and knowledge on how to carry out a given assessment or process, rather than more specific variables and mappings that require much effort if they are to be used in other contexts.

With the help of various tools and techniques, these frameworks have explored various means of expressing environmental and economic results. In some cases, the economic analysis included costs of environmental externalities, and material/process costs (for LCC). The environmental analysis included the impacts of the environmental burdens of specific processes and products, measured in the different impact categories (for LCA). Notwithstanding, monetization of environmental impacts has been widely used in existing frameworks, trying to translate environmental impacts into economic ones. This seems to have been the main path for LCA-LCC integration.

However, innovative approaches, using MCDA and fuzzy logic (for example) have opened up new opportunities for integrating environmental and economic outcomes. A noteworthy study in this regard is the fuzzy inference framework proposed by Kouloumpis and Azapagic (2018) that integrates LCA, LCC, and SLCA, in which the results are turned into linguistic variables and a sustainability assessment is performed on the same basis. This translation, which allows all the variables to be judged on the basis of the same unit, enables a better assessment of possible trade-offs. However, it can still be misleading, depending on possible biases related to the unit of analysis.

Miah et al. (2017) reported that the integration of LCA and LCC into frameworks has occurred on the basis of a few approaches, including independent LCA and LCC as part of an overarching framework, independent LCA and LCC analysis integrated by MCDA, optimization of LCA and LCC analysis, environmental LCC, and eco-efficiency. These approaches seem to be able to typify the plethora of frameworks available in the existing literature. Drawing on that, the evolution of frameworks seem to have sought covering limitations such as weak integration of LCA and LCC, ill-designed (arbitrary or unintentional) focus on either LCA or LCC in environmental-economic assessments, lack of standardization of LCA-LCC analysis, inadequate environmental-economic information for decision-making, lack of clear guidance for handling conflicting perspectives, and for managing subjective assessments.

Overall, it is no easy task to point out the best framework for the integration of LCA and LCC. Both tools are used across a range of sectors, with various underlying intentions, and they might be used by individuals with varying degrees of understanding of LCA and/or LCC. These comprise some of the concerning matters that need to be accounted for when designing and using a framework that integrates LCA and LCC.

Based on what could be gathered from the existing literature/practice, in order to build a framework that is both useful and simple, one should consider that it (i) should be able to be used by people with limited knowledge on both LCA and LCC; (ii) is complete enough to allow informed decision-making but also simple enough to enable resource- and time-feasibility even when a massive amount of products (or systems) are assessed at the same time; (iii) should account for monetization of environmental impacts, since these are then likely to be more easily incorporated into the decision-making process.

4.3 Challenges to LCA-LCC integration

Environmental burdens and associated resource consumption represent major challenges to the achievement of sustainable development (Cao et al. 2019), and therefore, obstacles and opportunities arise when LCA and LCC are combined. Modern producers can simultaneously reduce the environmental impacts of their products and achieve economic benefits by balancing the trade-offs between the economy and the environment to ensure business continuity (Ameli et al. 2017). In view of this, environmental benefits and economic consequences are often assessed through a combined LCA and LCC eco-efficiency assessment (Zhang et al. 2019). On these notes, several *challenges* in relation to the integration of LCA and LCC can be mentioned.

4.3.1 Both LCA and LCC are time- and resource-intensive

When it comes to LCA and LCC, one issue that prevents more widespread use of both is that their implementation is time and resource-intensive, and analyses are often conducted separately (Rodrigues et al. 2018). Resources such as economic investment and human knowledge are needed to carry out the analyses of both tools. For an LCA study, for instance, if time is of the essence, then greater investments are necessary to speed up the analysis and more people need to be involved, with knowledge of both the tool and the system under study.

There have been existing attempts to overcome the challenge of resource-intensiveness in literature/practice. One can mention the looming of simplified versions of a life cycle assessment even at the early stages of LCA development, in the 1990s. Screening or streamlining LCAs have been used to identify key issues in the environmental profile of products, rather than a full LCA, for reasons such as time and/or budget constraints, as well as for, at times, seeming to be more cost effective (see Bretz and Frankhauser 1996; Curran and Young 1996; Fleischer and Schmidt 1997; Svensson and Ekvall 1995). The same can be said to be true for life cycle cost assessments. At least since the late 1970s it is possible to observe the concern with simplifying LCC analyses, from procedures that allowed using simple tools as handheld calculators (see Mills 1979), to integrating it into product development (see Reed 1986). Even though these simplified analyses can still be observed currently (see e.g. Rodrigues et al. 2018), no definite one has been widespread.

4.3.2 Both LCA and LCC are knowledge intensive

People involved in the analyses need to have knowledge and skills to act in different contexts and perspectives into adjoining LCA and LCC. Science has developed its own vocabulary, with specific terms and meanings (Heijungs 2014). The same is true for LCC, thus both analyses require prior knowledge in order for the application to be consistent and the results to be reliable.

Although there may be standards to guide the analyses, adequate knowledge of both LCA and LCC is necessary to be able to detect their overlaps and differences within a system. Careers in the field of LCA end up as consultants and specialists, but also with basic research, focusing on increasing opportunities to develop the integration of LCA and LCC. Another approach to expand the knowledge on a life cycle perspective in the academic environment are the courses that involve case studies with applied LCAs, such as observed in Aurandt and Butler (2011), Lockrey and Johnson (2013), and Gilmore (2016). One further important remark is that both LCC (Gluch and Baumann 2004) and LCA (Rex and Baumann 2008) are enablers of great learning (thus knowledge acquisition) opportunities. Learning about economic and environmental issues in general can be of interest to understand market behavior or to identify possibilities for improvement based on these approaches.

4.3.3 Monetizing environmental impacts

An extensive practice for integrating LCA and LCC is monetization. However, monetizing environmental issues is not simple. Monetary flows represent direct costs and benefits, impacting the decision maker (Miah et al. 2017), and although the costs are given in a specific currency, as one component of the life-cycle cost of a product (Afrane and Ntiamoah 2012), there are no established rules about (for example) whether the value of money should be considered over time, how long environmental impacts should be accounted for when monetizing, and whether all impacts can be monetized or not.

Moreover, although resources such as ISO 14007 (ISO 2019a) and ISO 14008 (ISO 2019b), which provide guidance on determining environmental costs and benefits, and monetary valuation of environmental impacts, have been made available recently, monetization is still an issue of concern due to its complexity, and it is rather soon to measure the impacts of the use and content of those standards thus far.

4.3.4 Lack of tools to integrate LCA and LCC

The need for integration has been highlighted since as early as the beginning of the 2000s (see Nakamura and Kondo 2006), and thus, the possibility of using the same software tool used in LCA studies to compile LCC results was hypothesized during the analysis of the studies in the final portfolio. However, there seems to be no studies mentioning any integration of LCC and LCA using the same software tool, for instance, using the LCA software tool to account for economic indicators along with environmental aspects when building a life cycle inventory. Therefore, this accounts for another challenge when integrating LCA and LCC.

Umer et al. (2017) corroborate that these tools require other tools to handle uncertainties and to support decision-making processes with reliable results. Although the construction sector represents the main area of publication when it comes to the integration of LCA and LCC (see Fig. 3), advances need to be made in the area, where, for example, software developers may develop a suitable BIM-LCA/LCC tool (see Santos et al. 2019). Moreover, due to the lack of tools to integrate LCA and LCC, it is also difficult to present a quick and easy technique/tool for managers in decision making. One such technique could (e.g.) include a graphical visualization of the results in LCA-LCC integration.

It has not been explicitly reported in the existing literature the reasons why LCA software tools (GaBi and Umberto, for instance), which have the built-in functionality of considering the associated costs of inputs, have not been used to conduct LCC assessments, in spite of there being recurrent claims on the need for integrating LCA and LCC in previous research efforts. On top of that, there is no mention of the implications to the studies' results for using or not those LCC-enabling functionalities.

4.3.5 Different scopes for LCA and LCC

Using different scopes for LCA and LCC will likely not make the results representative of the same system, beyond making data collection and analysis more complicated when compared to the same scope. In fact, an integration of LCA and LCC seems beneficial. Something to note is that both tools may share the scope and system boundaries (Di Maria et al. 2018), but disagree on the source and format of the data.

Nonetheless, once again, it is highlighted the lack of standardization for their coupled use. If, on the one hand, there are two standards for LCA (ISO 14040 and 14044), on the other hand, LCC does not present a faithful standard to be followed. If an organization aims for an integrated LCA and LCC study for a particular asset, only when the organization owns the asset the potential environmental impacts are accounted for, thus outsourced activities might not be part of the scope. However, costs such as for maintenance (e.g.) of that particular asset (thus costs of outsourced activities) might be included in the LCC study.0

4.3.6 Higher volatility of economic data compared to environmental data

Economic data is more volatile than environmental data. Changes in the economy are fast and can make economic data obsolete with the same speed. Environmental data can also turn obsolete with new discoveries or updates in databases with more regional data (for instance); however, the rate of volatility or obsolescence of environmental data is not as high as that of the economic data.

The implications of the volatility of environmental data and information have been studied from different perspectives, such as implications to product development (see Barry et al. 2006), or to the long-term results of entire organizations (see Hoti et al. 2008). Dugal and Gopalakrishnam (2000) argue that, ultimately, volatility is good, as it might help assess the need to update data or information given the aspects that make it volatile, and their study still reveals that environmental volatility affects economic decisions, on a sustainable perspective. Volatility of economic data, in turn, has been researched more in depth and extensively (see, e.g., Edwards and Thames 2010; Tang 2019; Yu 2014) and has been used as one more variable to guide organizational decision-making (see Chichilnisky and Gorbachev 2004). Nonetheless, although the relationship between environmental and economic volatility is not clear, it is noted that their volatility differs, with economic volatility being believed to be higher than environmental volatility, which brings about one more factor to be accounted for when coupling environmental and economic data.

4.3.7 Differences in environmental and economic background data

The economic data (e.g., price of a good) already includes all the background monetary flows needed to produce that good. Physical flows of background processes, however, are not implied when analyzing the production of a certain product; thus, there might be differences in the impacts being calculated to a certain good depending on the environmental background data of its inputs. Externality costs can be estimated (e.g.) based on CO_2, CH_4, N_2O, and other emissions (see Martinez-Sanchez et al. 2017). Among others, LCC aims to estimate the costs of operation, maintenance, and final disposal (Hunkeler et al. 2008), while LCA aims to estimate potential environmental impacts (Guinee et al. 2011). Therefore, one might want to account for all these differences on how far back the data goes when coupling environmental and economic data.

4.4 Opportunities to LCA-LCC integration

Following the range of challenges presented in the previous section, a few *opportunities* can also be spotted on the integration of LCA and LCC, thus encouraging or facilitating the integration of these tools. Albeit not as many as the existing challenges, these few opportunities are presented hereafter.

4.4.1 Common system boundaries for LCA and LCC

It is stated by Reich (2005) that the discrepancies in system boundaries between LCA and LCC studies are not insurmountable, and it seems that for the greatest part of the existing studies seeking to integrate LCA and LCC the same system boundaries are used for both the LCA and LCC analyses. This can easily be observed in a range of studies (see, e.g., Lee et al. 2016; Petit-Boix et al. 2017a; Ramos et al. 2020; Zhang et al. 2019). Moreover, defining the same system boundaries to calculate environmental and economic potential impacts simplifies the integrated study (to some extent) and makes the integration of LCA and LCC easier. Integrating LCA and LCC becomes easier when defining the same objective and scope for both studies, also due to jointly collecting environmental and economic data.

Similar to LCA, LCC can also be analyzed in each phase of the life cycle of a good or service. Moreover, when LCA and LCC have the same scope, the entire set of assumptions can be established at once, together with the definition of objective and scope. In addition, the results may be presented to stakeholders graphically, illustrating the system boundaries, on top of showing environmental and economic impact at each stage of the life cycle and in each activity.

4.4.2 Benefitting from LCA structure to conduct LCC

In the analysis of LCC methodologies, it was possible to observe a pattern. Some studies used a structure similar to that of an LCA. For instance, Fazeni et al. (2014), Simões et al. (2016), and Simões et al. (2013a), used the following structure to conduct their LCC assessments: definition of objective and scope, analysis of revenues and costs, cost evaluation, and interpretation.

It is not uncommon to observe studies that report having merged specific cost assessment guidelines with LCA standards ISO 14040 and 14044 (ISO 2006a, 2006b). Examples to be cited are Ramos et al. (2020), who used ISO 15663-1 (ISO 2001a), ISO 15663-2 (ISO 2001b), and ISO

15663-3 (ISO 2001c) for gas-industry-based products; and Lorenzo-Toja et al. (2016), Miah et al. (2017), Petit-Boix et al. (2017a), Santos et al. (2020a), Zhang et al. (2019), and Zhang et al. (2020b), who used ISO 15686-5 (ISO 2017) for civil construction elements. Moreover, a frequent strategy is to follow the orientation provided by the Society of Environmental Toxicology and Chemistry (SETAC)'s "Environmental Life Cycle Costing: A Code of Practice" (Swarr et al. 2011). The referred document is aligned with the guidelines of ISO 14040 (ISO 2006a), and has been the guide of many studies integrating LCA and LCC (see, e.g., Muñoz et al. 2019).

As both tools consider a life cycle thinking perspective (Paes et al. 2020) and LCA is well-established, it only makes sense to resort to the well-established LCA structure when no specific guidelines are available for the LCC study. Furthermore, LCA has even been recognized as a prerequisite for cost accounting (Shapiro 2001). Even though using a similar (or the same) structure/methodological steps is no guarantee of synergy, given the lack of standardization for integrating LCA and LCC, such practice brings an opportunity for a closer alignment between those tools.

To date, a reasonable number of studies based on a life-cycle perspective was conceived in order to give answers to some of the challenges that constitute sustainable development (Lorenzo-Toja et al. 2016). However, opportunities and advances in scientific research in the area are yet to come.

5 Final considerations and future agenda

This study sought to review and analyze the progress in issues related to the integration of LCA and LCC. The number of research papers that seek to integrate LCA and LCC has grown considerably in recent years. The most relevant authors, countries, institutions, areas, journals, research topics, category of study, LCIA methods, system boundaries, standards, and software tools helped to provide a picture of where and under what contexts the studies have been conducted.

The use of LCA (from a best benefit point of view) should be mainly given for comparing projects, products, and processes at the early stages of development; however, what is largely done is to use an LCA study to assess already established systems. Although there is standardization for structuring an LCA study, it is still possible to observe a large number of studies that do not yet adopt or follow ISO standards (ISO 14040 and ISO 14044). The use of LCC, in turn, could be even more difficult, as there is no universally accepted (or adequate) standardization for all areas. However, it seems that the construction sector has devoted the most effort to this type of analysis. In the case of LCC, the influence of currency fluctuation over time could also be observed. Currency variation gives rise to uncertainties in the studies; in this regard, researchers have used various instruments to minimize the effects of uncertainty. Uncertainty and sensitivity analyses are widely recommended for these problems.

From the point of view of the integration of LCA and LCC, there is a lack of normatization in the use of methods, instruments and/or techniques to carry out studies with a combined approach. The use of multi-criteria analysis is crucial for integrating LCA and LCC. By minimizing the trade-offs between environmental and economic approaches, organizations can make better choices of products, services and processes, balancing the impacts of both dimensions by providing a higher level of information for decision-making.

This study has highlighted possible future directions based on some of the identified academic and practical gaps, mainly regarding the challenges identified for the integration of LCA and LCC. In addition, it is recommended that future research should investigate the standardization of structures and methodologies and the inclusion of social impact assessment on a broader life cycle perspective. With more efficient choices for products and processes, companies can gauge advantage over competitors while achieving greater sustainability. Moreover, it might be worth investigating in future research endeavors how developments on the integration of LCA and LCC have occurred differently in different countries and regions of the world, and the potential motivations for disparities.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 2 Characteristics of the articles

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Integrating life cycle cost analysis and LCA	Norris (2001)	*	US	Academic	Methodology proposal	The International Journal of Life Cycle Assessment	4.307	449	404.004
Sustainability assessment of energy systems: integrating environmental, economic and social aspects	Santoyo-Castelazo and Azapagic (2014)	The University of Manchester	UK	Energy	Methodology proposal	Journal of Cleaner Production	7.246	357	377.007
Bridging the gap between LCA, LCC and CBA as sustainability assessment tools	Hoogmartens et al. (2014)	Hasselt University	Belgium	Industrial	Review	Environmental Impact Assessment Review	4.135	156	176.004
Multiobjective optimisation of energy systems and building envelope retrofit in a residential community	Wu et al. (2017)	Swiss Federal Institute of Technology Zurich	Swiss	Energy	Methodology proposal	Applied Energy	8.848	111	146.009
Energy–environment–economy assessment of waste management systems from a life cycle perspective: Model development and case study	Dong et al. (2014)	Zhejiang University	China	Waste management	Case study	Applied Energy	8.848	113	133.009
Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review	De Luca et al. (2017)	Mediterranean University of Reggio Calabria	Italy	Agriculture	Review	Science of The Total Environment	6.551	74	109.007
Benchmarking wastewater treatment plants under an eco-efficiency perspective	Lorenzo-Toja et al. (2016)	University of Santiago de Compostela	Spain	Waste management	Case study	Science of the Total Environment	6.551	73	103.007

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Innovative olive-growing models: an environmental and economic assessment	De Gennaro et al. (2012)	University of Bari Aldo Moro	Italy	Agriculture	Case study	Journal of Cleaner Production	7.246	92	102.007
Increasing product value by integrating environmental impact, costs and customer valuation	Bovea and Vidal (2004)	Jaume I University	Spain	Academic	Methodology proposal	Resources, Conservation and Recycling	8.086	130	100.008
Life cycle engineering methodology applied to material selection, a fender case study	Ribeiro et al. (2008)	Technical University of Lisbon	Portugal	Industrial	Case study	Journal of Cleaner Production	7.246	110	100.007
An extended life cycle analysis of packaging systems for fruit and vegetable transport in Europe	Albrecht et al. (2013)	University of Stuttgart	Germany	Logistics	Case study	The International Journal of Life Cycle Assessment	4.307	82	97.004
Application of life cycle thinking towards sustainable cities: A review	Petit-Boix et al. (2017b)	The Autonomous University of Barcelona	Spain	Construction	Review	Journal of Cleaner Production	7.246	57	92.007
Integration of LCA and LCC analysis within a BIM-based environment	Santos et al. (2019)	Vrije University of Brussels	Belgium	Construction	Framework proposal	Automation in Construction	5.669	46	91.006
Environmental costs and benefits in life cycle costing	Steen (2005)	Chalmers University of Technology	Sweden	Academic	Methodology proposal	Management of Environmental Quality	0.000	116	91.000
Towards integrated sustainability assessment for energetic use of biomass: A state of the art evaluation of assessment tools	Buytaert et al. (2011)	Flemish Institute for Technological Research	Belgium	Energy	Review	Renewable and Sustainable Energy Reviews	1.110	85	90.012

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Integrating life cycle costing and life cycle assessment using extended material flow cost accounting	Bierer et al. (2015)	Chemnitz University of Technology	Germany	Academic	Methodology proposal	Journal of Cleaner Production	7.246	65	90.007
Modeling and optimization of building mix and energy supply technology for urban districts	Best et al. (2015)	Stanford University	US	Construction	Case study	Applied Energy	8.848	63	88.009
Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation	Braulio-Gonzalo and Bovea (2017)	Jaume I University	Spain	Construction	Methodology proposal	Energy and Buildings	4.495	48	83.004
Optimization of transit bus fleet's life cycle assessment impacts with alternative fuel options	Ercan et al. (2015)	University of Central Florida	US	Energy	Case study	Energy	6.082	55	80.006
A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing	Miah et al. (2017)	The University of Sheffield	UK	Academic	Framework proposal	Journal of Cleaner Production	7.246	40	75.007
How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation	Zanghelini et al. (2018)	Universidade Federal de Santa Catarina	Brazil	Academic	Review	Journal of Cleaner Production	7.246	37	72.007
Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions	Lidicker et al. (2012)	University of California	US	Construction	Case study	Journal of Infrastructure Systems	0.000	61	71.000

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings	Islam et al. (2015)	Royal Melbourne Institute of Technology	Australia	Construction	Case study	Energy and Buildings	4.867	43	68.005
Economic and environmental assessment of office building rainwater harvesting systems in various U.S. Cities	Wang and Zimmerman (2015)	Yale University	US	Waste management	Case study	Environmental Science and Technology	7.864	42	67.008
Environmental and economic implications of distributed additive manufacturing: The case of injection mold tooling	Huang et al. (2017)	Northwestern University	US	Industrial	Case study	Journal of Industrial Ecology	6.539	32	67.007
Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials	Akhtar et al. (2015)	The University of British Columbia	Canada	Waste management	Case study	Clean Technologies and Environmental Policy	2.429	42	67.002
Environmental and cost optimal design of a biomass–Wind–PV electricity generation system	Gonzalez et al. (2018)	The Polytechnic University of Catalonia	Spain	Energy	Methodology proposal	Renewable Energy	6.274	26	66.006
Carbon footprint and Life Cycle Costing of beef cattle in the Brazilian midwest	Florindo et al. (2017)	Federal University of Mato Grosso do Sul	Brazil	Agriculture	Case study	Journal of Cleaner Production	7.246	28	63.007
Economic and environmental potential for solar assisted central heating plants in the EU residential sector: Contribution to the 2030 climate and energy EU agenda	Tulus et al. (2019)	Rovira i Virgili University	Spain	Energy	Case study	Applied Energy	8.848	17	62.009

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability	Santos et al. (2017)	The French Institute of Science and Technology for Transport, Development and Networks	France	Construction	Methodology proposal	Journal of Cleaner Production	7.246	25	60.007
Evaluating eco-efficiency of 3D printing in the aeronautic industry	Mami et al. (2017)	Polytechnique Montreal	Canada	Industrial	Case study	Journal of Industrial Ecology	6.539	25	60.007
A multi-objective feedback approach for evaluating sequential conceptual building design decisions	Basbagill et al. (2014)	Stanford University	US	Construction	Methodology proposal	Automation in Construction	5.669	39	59.006
Eco-efficiency for greenhouse gas emissions mitigation of municipal solid waste management: A case study of Tianjin, China	Zhao et al. (2011)	Liaoning University of Technology	China	Waste management	Methodology proposal	Waste Management	5.448	54	59.005
Comparative eco-efficiency analysis on asphalt pavement rehabilitation alternatives: Hot in-place recycling and milling-and-filling	Cao et al. (2019)	The Hong Kong Polytechnic University	Hong Kong	Construction	Case study	Journal of Cleaner Production	7.246	13	58.007
BIM-based life cycle assessment and life cycle costing of an office building in Western Europe	Santos et al. (2020b)	Vrije University of Brussels	Belgium	Construction	Methodology proposal	Building and Environment	4.971	8	58.005
Life cycle tools within Ford of Europe's product sustainability index case study Ford S-MAX & Ford Galaxy	Schmidt (2006)	Ford Werke AG	Germany	Logistics	Case study	The International Journal of Life Cycle Assessment	4.307	78	58.004

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Parametric modeling approach for economic and environmental life cycle assessment of medium-duty truck electrification	Lee and Thomas (2017)	Argonne National Laboratory	US	Industrial	Case study	Journal of Cleaner Production	7.246	22	57.007
Integrating Environmental and Economic Sustainability in New Building Construction and Retrofits	Fregonara et al. (2016)	The Polytechnic University of Turin	Italy	Construction	Case study	Journal of Urban Technology	3.733	27	57.004
Life cycle and life cycle cost implications of integrated phase change materials in office buildings	Konstantinidou et al. (2019)	Aristotle University of Thessaloniki	Greece	Construction	Case study	International Journal of Energy Research	3.714	12	57.004
Environmental and economic comparison of reusable and disposable blood pressure cuffs in multiple clinical settings	Sanchez et al. (2020)	Northeastern University	US	Healthcare	Case study	Resources, Conservation and Recycling	8.086	6	56.008
A multi-objective optimization model for determining the building design and occupant behaviors based on energy, economic, and environmental performance	Hong et al. (2019)	Yonsei University	South Korea	Construction	Case study	Energy	6.082	11	56.006
Environmental and economic performance of plasma gasification in Enhanced Landfill Mining	Danthurebandara et al. (2015b)	Catholic University of Leuven	Belgium	Waste management	Case study	Waste Management	5.448	31	56.005

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Using life cycle sustainability assessment to trade off sourcing strategies for humanitarian relief items	Van Kempen et al. (2017)	VU University Amsterdam	The Netherlands	Logistics	Case study	The International Journal of Life Cycle Assessment	4.307	21	56.004
Integrating environmental and economic life cycle analysis in product development: a material selection case study	Simões et al. (2013b)	University of Minho	Portugal	Industrial	Case study	The International Journal of Life Cycle Assessment	4.307	41	56.004
Is SCENA a good approach for side-stream integrated treatment from an environmental and economic point of view?	Longo et al. (2017)	University of Santiago de Compostela	Spain	Waste management	Case study	Water Research	9.130	20	55.009
Navigating environmental, economic, and technological trade-offs in the design and operation of submerged anaerobic membrane bioreactors (AnMBRs)	Pretel et al. (2015)	Polytechnic University of Valencia	Spain	Waste management	Methodology proposal	Water research	9.130	30	55.009
Municipal solid waste management: Integrated analysis of environmental and economic indicators based on life cycle assessment	Paes et al. (2020)	Getulio Vargas Foundation	Brazil	Waste management	Framework proposal	Journal of Cleaner Production	7.246	5	55.007

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Prospective environmental and economic assessment of solar-assisted thermal energy recovery from wastewater through a sequencing batch biofilter granular reactor	Muñoz et al. (2019)	2.0 LCA Consultants	Denmark	Energy	Case study	Journal of Cleaner Production	7.246	10	55.007
Valorization of thermal treatment residues in enhanced landfill mining: environmental and economic evaluation	Danthurebandara et al. (2015a)	Catholic University of Leuven	Belgium	Waste management	Case study	Journal of Cleaner Production	7.246	30	55.007
Environmental and economic performance of an integrated municipal solid waste treatment: A Chinese case study	Wang et al. (2020)	Anhui Polytechnic University	China	Waste management	Case study	Science of the Total Environment	6.551	5	55.007
The Need for a Preference-Based Multicriteria Prioritization Framework in Life Cycle Sustainability Assessment	Grubert (2017)	Stanford University	US	Academic	Methodology proposal	Journal of Industrial Ecology	6.539	20	55.007
A Parametric Life Cycle Modeling Framework for Identifying Research Development Priorities of Emerging Technologies: A Case Study of Additive Manufacturing	Yao and Huang (2019)	North Caroline State University	US	Academic	Framework proposal	Procedia CIRP	0.000	10	55.000

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Synergistic generation of energy and water in remote communities: Economic and environmental assessment of current situation and future scenarios	Aberilla et al. (2020)	The University of Manchester	UK	Energy	Case study	Energy Conversion and Management	8.208	3	53.008
Eco-efficiency assessment of technological innovations in high-grade concrete recycling	Zhang et al. (2019)	Leiden University	The Netherlands	Construction	Case study	Resources, Conservation and Recycling	8.086	8	53.008
Development of a BIM-based Environmental and Economic Life Cycle Assessment tool	Santos et al. (2020a)	Vrije University of Brussels	Belgium	Construction	Methodology proposal	Journal of Cleaner Production	7.246	3	53.007
Life cycle greenhouse gas emission and cost analysis of prefabricated concrete building façade elements	Zhang et al. (2020a)	Leiden University	The Netherlands	Construction	Case study	Journal of Industrial Ecology	6.539	3	53.007
Trade-off between the economic and environmental impact of different decarbonisation strategies for residential buildings	Conci et al. (2019)	Technische University Darmstadt	Germany	Construction	Case study	Building and Environment	4.971	8	53.005
An integrated environmental and cost assessment method based on LCA and LCC for automobile interior and exterior trim design scheme optimization	Zhang et al. (2020b)	Hefei University of Technology	China	Industrial	Case study	The International Journal of Life Cycle Assessment	4.307	2	52.004
Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies	Harris et al. (2018)	Queen's University Belfast	UK	Energy	Methodology proposal	Renewable and Sustainable Energy Reviews	12.110	11	51.012

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Environmental and socio-economic assessment of cork waste gasification: Life cycle and cost analysis	Ramos et al. (2020)	University of Porto	Portugal	Waste management	Case study	Journal of Cleaner Production	7.246	1	51.007
Life cycle assessment and multi-criteria analysis of sugar-cane biorefinery scenarios: Finding a sustainable solution for the South African sugar industry	Nieder-Heitmann et al. (2019)	Stellenbosch University	South Africa	Agriculture	Case study	Journal of Cleaner Production	7.246	6	51.007
Streamlined environmental and cost life-cycle approach for building thermal retrofits: A case of residential buildings in South European climates	Rodrigues et al. (2018)	University of Coimbra	Portugal	Construction	Methodology proposal	Journal of Cleaner Production	7.246	11	51.007
Framework for construction system selection based on life cycle cost and sustainability assessment	Abou-Hamad and Abu-Hamd (2019)	Cairo University	Egypt	Construction	Methodology proposal	Journal of Cleaner Production	7.246	5	50.007
Eco-efficiency improvement of Western Australian remote area power supply	Arceo et al. (2019)	Curtin University	Australia	Energy	Methodology proposal	Journal of Cleaner Production	7.246	5	50.007
Environmental and economic performance of a car component: assessing new materials, processes and designs	Simões et al. (2016)	University of Minho	Portugal	Industrial	Case study	Journal of Cleaner Production	7.246	20	50.007

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Consequential LCA and LCC using linear programming: an illustrative example of biorefineries	Budzinski et al. (2019)	Helmholtz Centre for Environmental Research	Germany	Industrial	Case study	The International Journal of Life Cycle Assessment	4.307	5	50.004
Proper selection of substrates and crops enhances the sustainability of Paris rooftop garden	Dorr et al. (2017)	Joint Research Unit	France	Agriculture	Case study	Agronomy for Sustainable Development	4.531	14	49.005
Integrated life cycle sustainability assessment using fuzzy inference: A novel FELICITA model	Kouloumpis and Azapagic (2018)	The University of Manchester	UK	Academic	Framework proposal	Sustainable Production and Consumption	3.660	9	49.004
Inclusive impact assessment for the sustainability of vegetable oil-based biodiesel–Part I: Linkage between inclusive impact index and life cycle sustainability assessment	Nguyen et al. (2017)	Osaka Prefecture University	Japan	Energy	Methodology proposal	Journal of Cleaner Production	7.246	13	48.007
Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions	Hasik et al. (2019)	University of Pittsburgh	US	Construction	Case study	Building and Environment	4.971	3	48.005
Sustainable Configuration of Bioretention Systems for Nutrient Management through Life-Cycle Assessment and Cost Analysis	Xu and Zhang (2019)	University of South Florida	US	Waste management	Case study	Journal of Environmental Engineering	1.264	3	48.001

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Application of the integrated ecodesign method using the GHG emission as a single indicator and its GHG recyclability	Lee et al. (2016)	Korea Railway Research Institute	South Korea	Logistics	Framework proposal	Journal of Cleaner Production	7.246	17	47.007
Integrating external costs with life cycle costs of emissions from tertiary treatment of municipal wastewater for reuse in cooling systems	Theregowda et al. (2016)	Transtech Engineering Consultants	US	Waste management	Case study	Journal of Cleaner Production	7.246	17	47.007
Life cycle based multi-criteria optimization for optimal allocation of commercial delivery truck fleet in the United States	Zhao et al. (2016)	University of Central Florida	US	Logistics	Case study	Sustainable Production and Consumption	3.660	17	47.004
Are we preventing flood damage eco-efficiently? An integrated method applied to post-disaster emergency actions	Petit-Boix et al. (2017a)	Autonomous University of Barcelona	Spain	Waste management	Case study	Science of The Total Environment	6.551	11	46.007
Sustainability evaluation framework for pavement technologies: An integrated life cycle economic and environmental trade-off analysis	Umer et al. (2017)	Alberta Transportation	Canada	Construction	Case study	Transportation Research Part D: Transport and Environment	4.577	11	46.005
Integrating life cycle assessment (LCA) and life cycle costing (LCC) in the early phases of aircraft structural design: an elevator case study	Calado et al. (2019)	University of Lisbon	Portugal	Industrial	Methodology proposal	The International Journal of Life Cycle Assessment	4.307	1	46.004

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
A sustainable method for optimizing product design with trade-off between life cycle cost and environmental impact	Ameli et al. (2017)	Amirkabir University of Technology	Iran	Industrial	Methodology proposal	Environment, Development and Sustainability	2.191	9	44.002
A normative decision analysis method for the sustainability-based design of products	Eddy et al. (2013)	University of Massachusetts	US	Industrial	Case study	Journal of Engineering Design	1.950	28	43.002
Taking the Time Characteristic into Account of Life Cycle Assessment: Method and Application for Buildings	Zhang (2017)	Zhejiang University of Technology	China	Construction	Methodology proposal	Sustainability	2.576	7	42.003
Environmental and economic assessment of a road safety product made with virgin and recycled HDPE: A comparative study	Simões et al. (2013a)	University of Minho	Portugal	Industrial	Case study	Journal of Environmental Management	5.647	26	41.006
Methodological advancements in life cycle process design: a preliminary outlook	Fazeni et al. (2014)	Johannes Kepler University Linz	Austria	Industrial	Methodology proposal	Resources, Conservation and Recycling	8.086	18	38.008
Hybrid LCC of appliances with different energy efficiency	Nakamura and Kondo (2006)	Waseda University	Japan	Industrial	Case study	The International Journal of Life Cycle Assessment	4.307	57	37.004
Life cycle costing as part of design for environment environmental business cases	Schmidt (2003)	Ford Werke AG	Germany	Academic	Methodology proposal	The International Journal of Life Cycle Assessment	4.307	68	33.004

Table 2 (continued)

Title	Reference	Institution	Country	Area	Type of study	Journal	IF	Citation	*InOrdinatio*
Two-scale evaluation of remediation technologies for a contaminated site by applying economic input–output life cycle assessment: Risk–cost, risk–energy consumption and risk–CO2 emission	Inoue and Katayama (2011)	Nagoya University	Japan	Agriculture	Case study	Journal of Hazardous Materials	9.038	26	31.009
Uncertainty analysis in the financial assessment of an integrated management system for restaurant and catering waste in Spain	Escobar et al. (2015)	Polytechnic University of Valencia	Spain	Waste management	Case study	The International Journal of Life Cycle Assessment	4.307	6	31.004
Integrated assessment of environmental and economic performance of chemical products using analytic hierarchy process approach	Yu et al. (2007)	South China University of Technology	China	Industrial	Case study	Chinese Journal of Chemical Engineering	2.627	42	27.003
Combining ecological and economic assessment of options for newspaper waste management	Dahlbo et al. (2007)	Finnish Environment Institute	Finland	Waste management	Case study	Resources, Conservation and Recycling	8.086	39	24.008
An integrated assessment of continuously reinforced and jointed plane concrete pavements	Muga et al. (2009)	University of South Florida	US	Construction	Framework proposal	Journal of Engineering, Design and Technology	0.000	25	20.000
Life cycle approach in the procurement process: The case of defence materiel	Hochschorner and Finnveden (2006)	KTH Royal Institute of Technology	Sweden	Academic	Review	The International Journal of Life Cycle Assessment	4.307	35	15.004

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