Implementing Life Cycle Sustainability Assessment in Building and Energy Retrofit Design—An Investigation into Challenges and Opportunities

Hashem Amini Toosi, Monica Lavagna, Fabrizio Leonforte, Claudio Del Pero, and Niccolò Aste

Abstract The built environment is known as a major contributor to both sustainability problems and solutions. Life Cycle Sustainability Assessment (LCSA) which is a promising approach to evaluating the environmental, economic, and social dimensions of building performance, is progressively drawing the building researcher's attention. This chapter aims to review the roots and evolution of building sustainability assessment and discusses the associated challenges of LCSA in building and energy retrofit design. Through a critical review, different assumptions and limitations will be reviewed, and the main challenges of integrating LCSA into building energy retrofit design will be classified and discussed. In the end, the new research lines such as developing integrated LCSA models, application of optimization methods, and Building Information Modeling (BIM) in LCSA will be discussed.

Keywords LCSA · LCA · LCC · SLCA · Decision-Making · Integrated Models · BIM

H. Amini Toosi (✉) · M. Lavagna · F. Leonforte · C. Del Pero · N. Aste
Architecture, Built Environment and Construction Engineering Department, Politecnico Di Milano, Via Ponzio 31, 20133 Milano, Italy
e-mail: hashem.amini@polimi.it

M. Lavagna
e-mail: monica.lavagna@polimi.it

F. Leonforte
e-mail: fabrizio.leonforte@polimi.it

C. Del Pero
e-mail: Claudio.delpero@polimi.it

N. Aste
e-mail: niccolo.aste@polimi.it

S. S. Muthu (ed.), *Life Cycle Sustainability Assessment (LCSA)*,
Environmental Footprints and Eco-design of Products and Processes,
https://doi.org/10.1007/978-981-16-4562-4_6

1 Introduction

The built environment is known as a significant contributor to both sustainability problems and solutions [1]. In such a context, the growing consensus about three facts is of paramount importance leading to progressive efforts in providing comprehensive standards and guidelines for the Life Cycle Sustainability Assessment (LCSA) in the building sector. First is the perception of sustainability as a multidimensional, interdisciplinary, and dynamic science. It requires continuous research to deliver a balanced understanding among various dimensions, including environment, economy, and social dimensions [2, 3]. The dynamism among sustainability pillars and their inherent intricacies demands providing up-to-date standards and guidelines as an indispensable requirement of the assessment works and continuous methodological development and improvement [3–5].

Second is the fact that the expansion of the building sector in response to the growing needs of housing and urbanization trends shows that the building sector is a key role player to achieve the sustainability targets in the present and the future [6, 7]. In the same context, the large share of existing buildings discloses the significant potential of building refurbishment strategies to reach sustainability in this sector [8].

Last but not least is that the building sector can no longer be considered as lineated life products. The building sector's life span is now being studied in the cradle to grave circular scheme by which its sustainability must be evaluated with a whole life cycle perspective [1].

However, various building sustainability assessment frameworks and standards have been released worldwide, a survey on their implementation level in the recent scientific publications is worthy of investigation. This research aims to review and discuss recent scientific publications in LCSA on building energy retrofitting. The goal is to enlighten the extent to which the current standards have been employed in the reviewed publications, the missing aspects (not developed in the standards), and propose scenarios for development and methodological implementation.

To achieve the purpose mentioned above, the published research papers in the field of LCSA in building energy retrofitting are critically reviewed and discussed with a focus on the scope and indicators coverage, the adopted assessment methodologies, weighting, and aggregation methods among LCSA pillars and the final decision-making procedures. The papers are reviewed in four categories containing LCA, LCC, SLCA, and multidimensional LCSA studies where the limitations and advances are critically discussed.

The initial results of the present review highlight that the main challenges in the published research papers could be attributed to (1) lack of required databases, (2) quantification and measurement problems in LCSA impact categories, (3) lack of including impact categories and indicators suggested by standards, and consequently (4) an unbalanced level of development in LCSA pillars evaluation. Also, the level of information provided in each study, both as the input data and the final results, do not match the standards recommendations. Moreover, the development of SLCA assessment methodologies and the synthesis among LCSA pillars through weighting and aggregation are found as vivid obstacles of LCSA application in the literature. These findings along with more issues found in this review, enlighten and explain the critical challenges of LCSA standards implementation in building energy retrofit studies. The data and information management, alongside the considerable computational time required for the in-depth assessment, are the main obstacles in applying LCSA in building energy retrofitting.

In this chapter, the root and evolution of the concept of sustainability over the last decade are studied. Later on, the advent of life cycle sustainability assessment in the building sector and its integration into decision-making methods in building design is reviewed and analyzed. Afterward, The application of LCSA in building energy retrofitting is critically discussed to highlight the main challenges and emerging opportunities in this field of study. The chapter continues with a detailed classification of the main observed challenges of LCSA implementation in building and energy retrofit design. In the end, after an in-depth review, the development of integrated frameworks coupled with optimization models and the integration of Building Information Modeling (BIM) is discussed as promising solutions for implementing LCSA into building and energy retrofit design.

2 Sustainability and Development; The Roots and Evolution

Although the term sustainability is widely used, there are still ambiguities and complexities in the concept of sustainability and sustainable development [9, 10]. This vagueness has been discussed over the years, and it is still being addressed in the academic environment. One possible reason that leads to these complexities is the fact that both sustainability and development are not static and have been evolving in response to the existing dynamism between society and nature [3–5]. The concept of sustainable development is initially driven from economic discipline in [11], where the concerns were about the capacity of limited natural resources to support the increasing human population. According to the Scopus database, the term sustainability was found in 70th, when it first emerged in the scientific literature of economic studies [11], however, some previous studies indicate that the use of this term dates back to a monograph published in 1713 to address the sustainable use of forest resources [2, 12].

As described in dictionaries, development refers to the gradual growth to become more advanced [13]. To clarify this general definition, several theories and interpretations have been proposed by scholars in different fields. One of the definitions collected by [5] elaborates development as a multidimensional process in which major changes in social structures, attitudes, and institutions as well as economic growth, inequality reduction, and poverty eradication are involved. Regarding the historical definitions, the term sustainability primarily addresses the economic-environmental aspects, while development is more oriented to socio-economic issues. Therefore, sustainable development could be interpreted as a concept addressing social, economic, and environmental issues. A similar interpretation is now widely accepted and used.

It is possible to track the efforts to interpret and standardize the term sustainability or sustainable development in the twentieth century. The United Nations conference on the human environment held in Stockholm, Sweden, in 1972, is known as the first international conference to deal with the concept of sustainability [14]. In the declaration of the Stockholm conference, 26 principals were agreed concerning human rights and responsibilities with respect to the social, environmental, and economic aspects. These principles demand an internationally collaborative action plan to achieve sustainable development principles worldwide. In this conference, 109 recommendations were provided to determine how the international participant should effectively regulate their actions to protect the human environment [15].

The World Commission on Environment and Development (WCED) provided the first definition of sustainable development in 1987. In the draft published by WCED, Sustainable development was defined as a *development that meets the needs of the pursuant without compromising the ability of the future generations to meet their needs*. This definition considers the limited ability of the environment to provide the present and future needs of humanity while highlighting that the economic and social requirements in all countries must also be defined in terms of sustainability [16].

An important UN Conference on Environment and Development (UNCED) was held in Rio de Janeiro, Brazil, in 1992 [17]. It is known as the first attempt to implement sustainable development from concept to an international action plan [12]. In the 4th principle of the Rio declaration, environmental protection is emphasized as an integral part of development. The 5th principle refers to eradicating poverty and standard of living as indispensable social requirements of sustainable development. The 12th principle promotes a supportive and open international economic system leading to economic growth for better addressing the problems of environmental degradation [18]. An overall review of the Rio declaration principles shows that environmental issues are the main concerns and the core of this declaration since most of the principles have aimed to promote practical environmental protection actions. Later in 2002, in the World Summit on Sustainable Development held in Johannesburg, South Africa, the balance between economic development, social development, and environmental development as interdependent and mutually reinforcing pillars of sustainability were reaffirmed [19].

Regarding the conflicts among three sustainability pillars and the unequal or insufficient progress in the three dimensions of sustainability, the United Nations Conference on Sustainable Development, Rio + 20 was held in Rio de Janeiro, Brazil, in 2012 [20], emphasizing the balance among sustainability pillars. In the report of this conference entitled "The future we want", poverty eradication is recognized as the greatest global challenge facing the world and an indispensable requirement for sustainable development [21]. In this report, the concept of the green economy is recognized as an essential tool that is available for achieving all pillars of sustainable development. A particular focus on the social aspect highlighted in this conference was also among the Millennium Development Goals, where six goals out of all eight proposed sustainable development goals were oriented to the social dimension of sustainability [22].

The following United Nations Sustainable Development Summit was held in New York in 2015. The resolution adopted by the General Assembly in UN on 25 September 2015 entitled "Transforming our world: the 2030 agenda for sustainable development, changed the traditional concept of sustainable development fundamentally [12] and set out 17 areas of sustainable development goals [23]. These areas are known as the last versions of Sustainable Development Goals (SDGs) declared by United Nations. The year 2015 was a distinguished historical point when the UN set out the 17 SDGs. Not only this step forward for better understanding SDGs and providing the bases of intergovernmental collaboration, but also the Paris Agreement on international effort to increase the abilities of countries in controlling the impacts of climate change [24], have been considered as the historical human efforts to build a more sustainable future.

As elaborated in this section, the definitions of sustainability and development have been subjected to several changes in their meaning and priorities over the last decades. The dynamism and evolving interaction between human society and the natural resources as a complex system could be recognized as the main reason for changing interpretation to define meanings and priorities in sustainability and development.

3 Sustainability Assessment of Buildings—A Life Cycle Approach

The concept of sustainable development targets all human activities and aspects of life and is expected to be adopted by public policy makers to regulate the socio-economic aspect of worldwide activities. It is particularly promoted and applied to address the issues related to the design of the built environment in the last decade [25].

The increasing need for housing in human societies resulting from population growth has led to a rapid expansion of the built environment [26]. The share of the building sector in final energy consumption and GHG emission are increasing worldwide. According to the statistics, the building sector is accounted for 36 and 39% of the final energy consumption and CO_2 emission globally [27]. These values have been estimated at 40 and 32% in European Union (EU), respectively [28].

Given the noticeable contribution of the built environment expansion to the environmental impacts [6, 7], economy, and societies [29] as three pillars of sustainable development [30], growing attention to this issue is now emerging in academies, industries, and policy programs. The increasing awareness about the building sector's considerable impacts on sustainability targets resulted in establishing standards and guidelines to reduce the environmental impacts in this sector. In this context, both the economic and social performance of the building sector has been pursued by emerging studies, as well as the environmental performance, to provide harmony and balance among three life cycle sustainability pillars [1]. However, the social dimension is the least addressed aspect of building sustainability in the literature [31], mainly due to simplifying the sustainability concept in buildings and reducing it to merely environmental sustainability. The terms sustainability and green buildings have been in use interchangeably in building science literature [31]. Consequently, the initial understanding of the term "green" as *"building design strategies that are less environmentally and ecologically damaging than typical practices"* [32], as well as the fact that environmental performance has been better surveyed and standardized [33], could be recognized as the main reasons explaining why all three sustainability dimensions are not equally developed and investigated in the building science literature.

Like the general concept of sustainability, the definition of sustainability in buildings has experienced various interpretations and evolution over the last decade. However, at least three sustainability pillars, such as environment, economy, and society, are now recognized as the widely accepted interpretation; the value judgment among these three pillars is still controversial. Looking at Green Building Rating Systems (GBRSs) such as LEED and BREEAM, the dominancy of a tendency to the environmental interpretation of green or sustainable building is observable [32].

On the other side, several guidelines have been published to standardize the assessment method of the sustainability in buildings with a life cycle approach such as BEES models [34] or the EN standards, including the framework of building sustainability assessment [35], the framework of environmental [36], social [37], and economic performance assessment [38]. However, these methods provided useful methods to measure the building performance regarding the sustainability pillars, but do not address how to make decisions systematically among alternatives with different environmental, economic, and social performances. For instance, BEES models propose a weighted-sum approach to assign a final index to each alternative based on its environmental and economic performance but stay silent about the weighting methods between economy and environment. Likewise, the EN standards have standardized the calculation methods to measure the environmental [39], economic [40], and social performance [41]; they do not clarify how the decision maker should compare different alternatives having conflicting results for each sustainability pillar.

The sustainability pillars in buildings are still being developed and discussed. For instance, looking at GBRSs, there are various aspects and credits, such as the integrative process in LEED or technical quality and process quality in DGNB, that cannot be attributed to the three traditional sustainability pillars. Likewise, recently a fourth dimension has drawn researchers' attention in the literature as institutional dimension [42, 43] that is defined as *"the results of interpersonal processes, such as communication and co-operation, resulting in information and systems of rules governing the interaction of members of a society"* [32].

The various interpretations of sustainability and the lack of accurate definition and calculation methods to quantifiably measure the sustainability pillars show that the sustainability assessment and life cycle sustainability assessment [44] in buildings are still open challenges that need to be more surveyed in the future studies.

4 Life Cycle Sustainability Assessment in the Decision Context—Challenges and Opportunities of Decision-Making Models in Building LCSA

The term Decision-Making (DM) model first emerged in the scientific publication of political science in 1959 [45, 46]. The application of this concept then got increasing attention in other fields as well. As a piece of evidence, the number of scientific publications referred to decision-making models/methods has increased from 2 to more than 15,500 between 1952 to 2020, with a significant growth rate over the recent years. As much as more complicated criteria entered human life, the higher necessity of comprehensive methods to make intelligent decisions is perceived. As a result, the application of DM methods is now widely accepted and is spreading to all fields from very early practice in politics [45] to recent implementation in advanced technologies [47].

Decision-making models are known as the most important application of mathematics in various human activity fields [48]. The necessity of advanced decision-making models arises when at least two assessment criteria exist, and these criteria are contradictory, or the solutions need a value judgment by stakeholders who might have conflicting interests [49].

Facing the global questions that encompass conflicting criteria, multiple diverse goals, contradictory interests, and targets with several different perspectives, Multi-Criteria Decision-Making Models (MCDMs) have been widely implemented to find the appropriate answers to contradictory questions [50]. Sustainability is of those areas that MCDMs models are applied to find comprehensive optimal solutions [51]. As already mentioned, sustainability appeared in the scientific literature in the 70th decade, while the first implementation of a DM model into the sustainability studies dated back to 1997, where it was applied to address the sustainability of future perspective of Swedish urban water systems [52].

Decision-making models in building life cycle sustainability assessment is a very new field of study compared to the comparatively short history of building LCSA. It also shows that building sustainability and life cycle sustainability of buildings were initially developed without taking all the benefits delivered by DM models. However, as LCSA and sustainability assessment include a higher level of complexity and a broader definition over the preceding years, more attention to implementing DM models emerges in the literature.

Amon all MCDM methods, several reviews concluded that AHP is the most popular and applied method in the literature [53, 54]. A study performed by [55] on MCDMs in sustainable energy development issues highlighted that AHP followed by TOPSIS is the most popular multi-criteria decision-making method in the literature.

This fact is also confirmed in our review of few papers published in the field of MCDMs in building life cycle sustainability assessment between 2010 to 2020. Table 1 summarizes the features of recent publications that have applied DM models in building life cycle sustainability starting from 2010 to 2020. In this review, those publications that applied decision-making models in building LCSA were reviewed to highlight the coverage level of LCSA pillars and find the most utilized decision-making methods. As shown in Table 1, most reviewed papers included all three sustainability pillars to evaluate the performance of different types of building design solutions such as structural systems and materials, HVAC systems, and building technologies.

Analytical Hierarchy Process (AHP) is found as the most applied MCDM method within the reviewed papers, while some authors have proposed hybrid DM methods to overcome the drawbacks of the single techniques in their studies [56, 57]. AHP was firstly developed by [58]. According to its developer, AHP is defined as "*a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales.* Saaty [59] proposed to decompose the decision process into four steps by which it would be possible to apply AHP in making decisions. These steps are [59]: (1) Definition of the problems and determine the kind of knowledge, (2) Structuring the decision hierarchy, (3) Constructing the pairwise comparison matrices, and then (4) Using the obtained weights to define the overall priority. AHP is known as a widely accepted and effective method to support decisions in the complex decision-making process by reducing the problems' complexity through transforming complicated problems into a set of simple comparisons and rankings [57], and increases the transparency and objectivity of decision-making as well as facilitating the detection of controversial items and providing data for establishing agreements [49].

Despite the advantages of the AHP method, one challenging issue associated with this method is that different hierarchies of criteria may affect and cause changes in weight allocations [55, 60]. Cinelli et al. [61] have concluded that although AHP is simple to understand and is well-supported by tools, as a drawback, it is cognitively demanding for decision makers' perspectives.

AHP assumes a full compensation among the criteria that means a low performance in one criterion could be entirely compensated by the high performance of other criteria [61]. While AHP is found as the most applied MCDM method to determine weights of criteria, TOPSIS is known as one of the most popular methods to rank alternatives in a decision-making process, thanks to its straightforward application [55]. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as developed by [67] is based on the concept that the selected alternative must have the shortest distance to the positive ideal solution while keeping the longest distance from the negative ideal solution [57]. Although TOPSIS is highly appreciated due to its easy application in problems with different sizes, some of its disadvantages are also addressed in the literature, such as not considering the correlation of attributes and its difficulty to weight attributes and keep the consistency of judgments [68].

These facts as fundamental critics about the most applied MCDMs in sustainability studies partially show why integrating MCDM methods in this research field could be

Table 1 The features of the recent application of DM models in building LCSA studies

Authors	Goal of analysis	Sustainability Pillars			DM model	Note
		Environment	Economy	Society		
Chandrakumar et al. [56]	Sanitation systems	✓	✓	✓	Fuzzy Analytical Hierarchy Process (FAHP)	Weights based on experts' views
Bakhoum and Brown [57]	Structural materials	✓	✓	✓	Hybrid AHP–TOPSIS–entropy methods	AHP to define weights, TOPSIS to rank alternatives, Entropy to evaluate weight factors of each phase of materials' life cycle
Liu and Qian [62]	Modular construction-based, Semi-prefabricated, Conventional method	✓	✓	✓	AHP-ELCTRE III	Weighting by CFPR-based AHP process, Ranking by ELECTRE method
Rashidi et al.[63]	Construction material supply chain	✓	✓	✓	Multi-attribute decision-making model, TOPSIS	AHP to define weights, TOPSIS to rank alternatives
Arroyo et al.[64]	HVAC systems	✓	✓	✓	Choosing By Advantages (CBA)	Weights assigned according to stakeholders' preferences
Medineckiene et al.[65]	Heating systems of buildings	✓	✓	✗	Complex Proportional Assessment (COPRAS)	AHP to define weights
Wang et al.[66]	Sustainable design options (building tech)	✓	✓	✗	MCDM	Direct weighting via questionnaire

called an open challenge. It is important to note that this paper does not aim to review all MCDM methods; in fact, the pros and cons of the most popular methods have been briefly discussed to understand the most common challenges of implementing decision-making models in sustainability assessment.

5 Implementing Life Cycle Sustainability Assessment in Buildings—The Case of Building Energy Refurbishment

This section reviews the published papers that addressed at least one dimension of life cycle sustainability assessment in building energy retrofitting to understand the methodological advancement, limitations, and challenges in this topic. Therefore, all the relevant papers published and indexed in Scopus and Elsevier until 2020 were retrieved and initially classified into three rubrics, including LCA, LCC, and SLCA studies. These papers are analyzed to clarify the adopted methodologies in each paper to provide a clear picture of the state of the art.

Figure 1 represents the number of papers published between 1989 to 2019 and their distribution around the world. As it is shown in this figure, the publication in this field is increasing fast during preceding years. The European countries, led by Sweden, Italy, Spain, and Portugal, followed by United States, Canada, and China, have the largest share in the research and publication of this field. The lack of LCSA research in several countries underlines that this research field is still not applied worldwide despite its significance in understanding global sustainability issues.

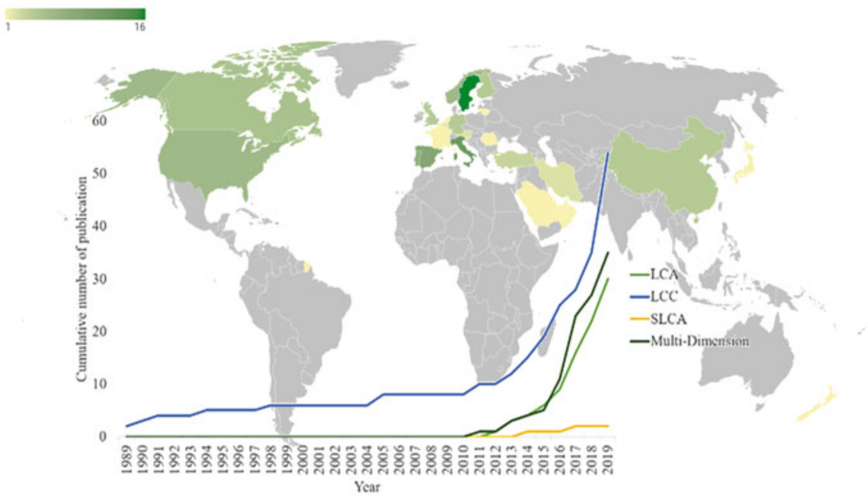

Fig. 1 Cumulative number of publications and their distribution in the world

5.1 LCA in Building Energy Retrofitting; A Review on Methods and Assumptions

Different assumptions and limitations in LCA studies make them difficult to be compared and interpreted against each other. A review is needed to be performed to highlight these assumptions, challenges, and new advancements within the research works related to LCA of building energy retrofit. This review provides essential bases to develop a comprehensive methodological framework for the application of LCA in building energy retrofit design.

Those papers that addressed the LCA of building energy retrofitting in the title or abstract were collected. By reviewing methods and materials in each paper, the challenges of LCA in building energy retrofit are discussed in this section. This part focuses on investigating uncertainties, inconsistencies, challenges, and methodological advances in LCA application in energy retrofit projects. These challenges might affect the reliability and comparability of LCA studies. Reviewing the assumptions and solutions in previous studies will provide a better perspective on how each LCA study could be integrated into the decision-making process of an energy retrofit design project.

One reported issue in previous LCA studies is how to standardize functional unit (FU) in LCA [69] of energy retrofitting which will be reviewed and discussed in this section. The different functional unit has been used in the reviewed papers. In the present review paper, four different kinds of functional units are found:

1. The energy demand/ consumption to provide the required level of thermal comfort [70].
2. The quantity of used materials in a system [71].
3. The unit of area or volume of the refurbished building [72].
4. The whole building under LCA [73].

According to the LCA standards, the functional unit must be clarified in the assessment report. In this review, we realized that some authors have not clearly shown the functional unit in their works, making their results impossible to be compared with other studies [39].

It is reported that the most popular system boundaries in LCA studies are cradle to grave [74]; this statement is also concluded and confirmed in the present review. Some researchers have limited the system boundary of the study solely to the overwhelming life cycle phases [75–77]. For instance, Mangan and Oral [78] limited their analysis to the production stage and use stage due to the lack of data in demolition and end-of-life stages. The system boundary limitation in the research is justified by the fact that previous studies have proven that these eliminated stages (demolition and end of life) have nearly 1 percent of total energy consumption in a building life cycle.

Some other researchers have included the whole building life cycle following the EN 15,978 standard [73, 79–81]. Regarding the reviewed papers in this section, it is found that most researchers have used the whole life cycle phases in their studies, while the lack of databases alongside the negligible impacts are seen as the main

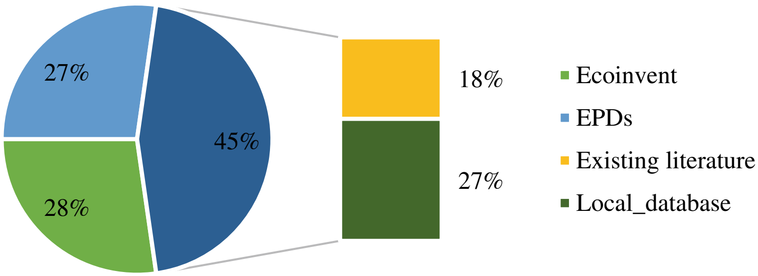

Fig. 2 Life cycle inventory databases used in the reviewed papers

reasons and justification for excluding some life cycle phases in the rest of the reviewed papers. An interesting research by Oregi et al. [82] showed a simplified LCA in which only the production and operation phases are covered could provide accurate results in designing energy retrofit scenarios.

LCI is known as one of the most complicated steps of an LCA study because of the vast numbers of inputs and missing data on materials and building components' environmental performance. In this review, some databases, such as Ecoinvent and EPDs, as well as existing literature or specific data reported by manufacturers, are found as the most common databases (Fig. 2). According to Oregi et al. [80], since different databases may have been prepared using various assumptions, it is essential to pay attention to the possible inconsistency of databases used in research.

Several environmental impact categories and indicators are proposed by LCA standards [39]; however, most published papers have only evaluated a small number of environmental impacts. It is stated that energy and global warming potential (GWP) is the most surveyed key performance indicator in previous studies; however, it is worthy of focusing and reviewing papers that have taken into account more indicators and study how they have been compared against each other. Most of the reviewed papers have only analyzed less than three environmental impact categories mainly due to simplifying the data acquiring procedure. Global warming potential and energy are the most evaluated impacts, as illustrated in Fig. 3.

De Larriva et al. [70] included two environmental indicators, Gross Energy Requirement (GER), and Global Warming Potential (GWP). They have stated that since the LCA is increasingly motivated by the climate change debate, they have chosen these two indicators.

The environmental impact categories in the study performed by Garcia-Perez [71] are limited to global warming potential and embodied energy. Ghose et al. [72] selected twelve environmental impacts recommended by EN 15,978 such as global warming potential, ozone depletion potential, photochemical oxidation potential, acidification potential, eutrophication potential, abiotic depletion (resources and fossil fuels) according to the CML impact assessment method. They also used UseTox method to evaluate human toxicity carcinogenic, human toxicity non-carcinogenic and ecotoxicity freshwater and ILCD 2011 + ReCipe method for particulate matter formation and ionizing radiation. The selection of these categories is in line with

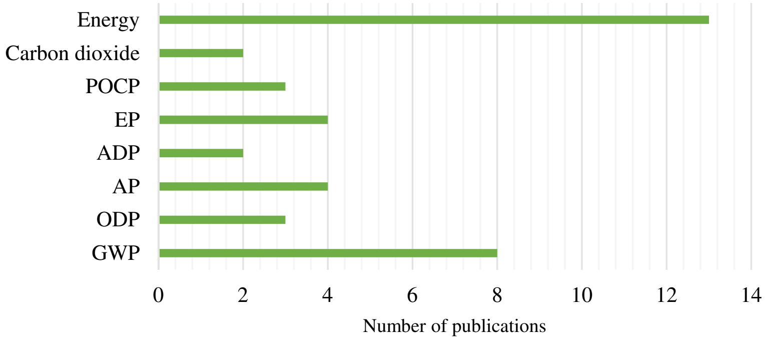

Fig. 3 Number of research papers that addressed each environmental impact. *Note* Energy refers to cumulative energy demand, non-renewable primary energy, embodied energy, life cycle energy and gross energy requirement

national recommendations in New Zealand, as they reported. In contrast, Mangan and Oral [78] and Marique and Rossi [79] only focused on life cycle energy and CO_2 emission. Oregi et al. [80] included only NonRenewable Primary Energy resources in their life cycle impact category. Valancius et al. [77] also included limited environmental indicators such as nonrenewable primary energy and CO_2 emission. Indicators in the study performed by Tadeu et al. [83] are limited to nonrenewable primary energy and greenhouse gas emissions over the building's life cycle.

For simplicity, Oregi et al. [82] considered only one indicator, which is "Use of nonrenewable primary energy sources." Managn and Koclar Oral [76] only took into account LCE and $LCCO_{2.}$ in their study. In the analysis performed by Valacius, Vilutiene, and Rogoza [77], only CO_2 emission and nonrenewable primary energy consumption over the building life cycle are taken into account. The research performed by Nydahl et al. [81] is focused on two environmental impact categories, including life cycle energy use and greenhouse gas emissions. Beccali et al. [73] considered six environmental impact categories at the level of mid-point indicators, including Cumulative Energy Demand (CED), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP).

The above-mentioned examples also confirm that, although most researchers have followed the LCA standards to calculate environmental impacts, only a few papers have analyzed all proposed environmental impacts by LCA standards. This limitation is mainly due to the lack of databases or with the aim of simplifying the calculation steps, which hopefully will be resolved by developing LCI databases and advancing the LCA software to facilitate the calculation process for non-expert users.

Finally, in some of the reviewed papers, some criteria that are almost neglected in the literature such as the different energy mixes in the future, have also been considered. Ghose et al. [72] have taken into account different energy mixes since, according to national energy programs, the share of fossil fuels is predicted to be reduced by implementing renewable energy sources in New Zealand.

5.2 LCC in Building Energy Retrofitting; Indicators and Economic Parameters

This section concentrates on the application of Life Cycle Cost (LCC) as a well-established method for the analysis of the economic performance of buildings [8, 84, 85]. The main parameters of LCC analysis in selected reviewed papers are discussed in this section, including the LCC indicator and economic parameters such as discount rate and energy price inflation rate in each paper.

Several economic indicators such as Net Present Value (NPV), Payback Period, Net Saving or Net Benefit, Saving to Investment Ratio, and Adjusted Internal Rate of Return are proposed by relevant standards [40]. Our review showed that NPV is the most used economic indicator in the reviewed papers (Fig. 4). Other economic indicators such as Value at Risk, Energy productivity, Net Present Cost, Net Saving, Saving to Investment Ratio, Adjusted Internal Rate of Return, Simply Pay Back Period are also adopted in different papers.

Taking accurate Discount Rate (DR) and Inflation Rate (IR) values is of paramount importance in economic assessments. A wide range of values both for the discount rate and inflation rate is found in the reviewed papers, while the EN 16,627:2015 proposes using the discount rate equal to 3 percent for the sake of comparability of the results of LCC studies. Some researchers have compared the LCC results by taking various values for discount and inflation rates in their studies [86–90]. For instance, Copiello, Gabrielli, and Boniaci [91] reported that the discount rate might affect the results four times as much as the energy price. They also mentioned that the discount rate might also affect the energy retrofit project by encouraging owners for higher initial investment. Our analysis shows that the values taken by researchers are usually higher than the 10-year average values which are reported by the countries.

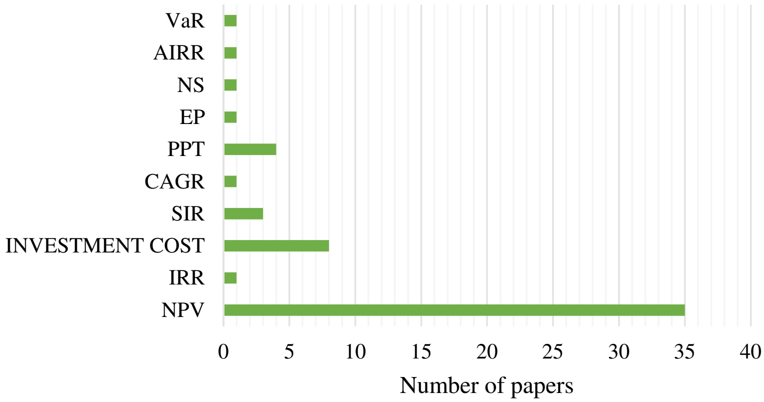

Fig. 4 Number of research papers that addressed each LCC indicator, Var: Value at Risk, AIRR: Adjusted Internal Rate of Return, NS: Net Saving, EP: Energy Productivity, PPT: Payback Period Time, CAGR: Compound Annual Growth Rate, SIR: Saving to Investment Ratio, IRR: Internal Rate of Return, NPV: Net Present Value

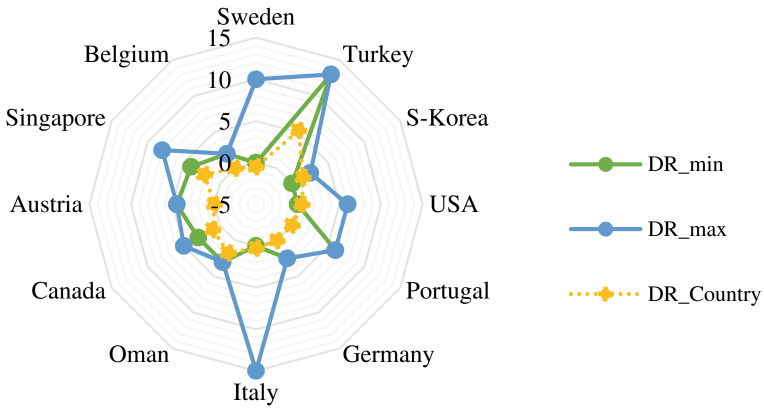

Fig. 5 The minimum, maximum discount rate (%) applied in the LCC studies in each country versus the 10-year average discount rate of the countries

As shown in Fig. 5, the minimum and maximum values of the discount rate applied in the research papers are higher than the actual average value of the discount rate in each country. Although it is worthy of investigation to analyze the influence of various DR values in research works, it is recommended to adopt the macroeconomic values according to the actual economic situation of the study project. Moreover, in compliance with the EN standards taking similar DR values in LCC studies in the building sector increases the comparability of the results. In case the researchers aim to conduct sensitivity analysis to evaluate the impact of the different economic situations on their project, the economic parameters should also represent the actual values in the projects' economic contexts and the relevant standards (e.g., Italian studies in Table 2, Figs. 5 and 6).

Regarding the values of discount rate and energy price inflation rate, Fig. 7 represents important information about the reviewed papers. As it is illustrated, most research works are performed with an energy price inflation rate lower than the average in all papers. However, a variety of discount rate values are considered in papers. Figure 7 shows that the papers published in different countries tend to conduct LCC analysis with a combination of low to a medium value of inflation rate and medium to high value for discount rate.

5.3 SLCA in Building Energy Retrofitting; The Implementation Level

Any adverse or beneficial change to the society or the quality of life that could be expressed with quantifiable indicators is defined as SLCA impact with respect to the following categories in EN 15,643-3:2012 [37]: accessibility, adaptability, health

Table 2 Summarizes the economic parameters applied in selected LCC studies in each country.

Countries	Discount rate			Energy price inflation rate			Country (electricity)
	Min	Max	Country	Min	Max	Country (gas)	
Austria [92]	4.5	4.5	0	–	–	–	–
Belgium [93]	2	2	0	3	3	4.392	4.39
Canada [94]	3	5	1	–	–	–	–
China [84, 95]	6.6	8					
Germany [96]	2.5	2.5	0	0	4	0.955	2.86
Italy [87, 88, 97–99]	0	15	0.25	0	4.5	0.562	2.104
Oman [100]	3	3	1.726	–	–	–	–
Portugal [101]	6	6	0	4	4	3.238	3.329
Singapore [89]	4	8	2.15				
Sweden [102–109]	0	10	−0.5	0.5	3	1.33	0.759
S. Korea [8, 110, 111]	0	2.54	1.5	–	–	–	–
Turkey [112–114]	13	13	5.25	–	–	–	–
United States [86, 115, 116]	0	6	0.5	5	5	2.233	0.6

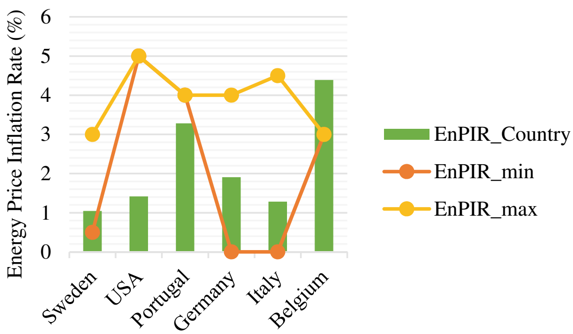

Fig. 6 The minimum, maximum Energy Price Inflation rate (%) applied in the LCC studies in each country versus the 10-year En-PIR of the countries (the average of gas and electricity price for end-user in residential buildings)

and comfort, loading and neighborhood, maintenance, safety/security, sourcing of material and services, and stakeholder involvement.

In the present review, no published research paper is found which directly addresses the social dimension of building energy retrofitting with a life cycle approach in the title, abstract, or keywords. However, few papers are found in which some social indicators such as thermal comfort [117], human live risk [118], and social feasibility [119] are taken into account. Thermal comfort could be considered as a social aspect of building sustainability assessment according to EN 15,643-3:2012 since it affects occupants and users' satisfaction levels. The studies performed

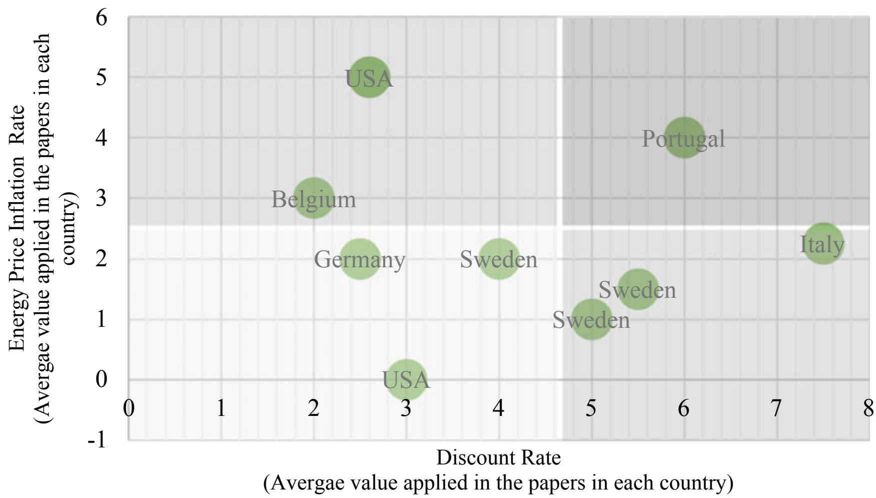

Fig. 7 The average of discount rate versus the average of energy-price inflation rate adopted in selected LCC studies in each country

by Assiego de Lavaria et al. [120] and Mostavi et al. [117] are of those few ones that have addressed one of the impact categories of social LCA in their assessment.

6 LCSA Challenges; A Classification of the Open Challenges and a Discussion on Emerging Solutions in the Literature

Several challenges are associated with sustainability assessment as a multidimensional interdisciplinary field of study [121]. However, taking a life cycle approach to sustainability assessment increases the study's comprehensiveness; it might result in a higher level of sophistication since more databases and assessment methods with a higher level of uncertainties and inconsistencies might be included in the analysis. Given the discussions in the previous sections and the research papers that addressed the sustainability assessment challenges within the last five years, the main challenges of measurement in life cycle sustainability assessment are presented and discussed in this section. Such a discussion helps to enlighten what aspects of LCSA need to be investigated and developed by further research works in the future.

The challenges associated with data collection and accessibility are constantly reported as one of the main obstacles in implementing life cycle sustainability assessment [1]. The required databases to conduct life cycle sustainability assessment are not readily available for specific materials, products, or services around the world [122–129] and the data acquisition procedure is not straightforward [126–134] due to the complexity of the data preparation and data-sharing challenges [124, 135].

Although databases have been developed during the last decade, the lack of data is still a barrier in this field. Moreover, the uncertainty caused by the missing data of emerging technologies alongside the uncertainties of measuring methods are known as important LCSA challenges [126, 134, 136–139].

A significant challenge of implementing LCSA is the fact that no consensus exists to establish or adopt a clear methodology to link the three dimensions of sustainability [1, 122, 129, 140–143]. The combination and harmonization among different metrics and measurement techniques [122, 139, 140, 143] alongside the different maturity levels of assessment methods for LCSA pillars [131, 136, 137, 144], specifically the weakness in developing the quantifiable measurement methods of the social dimension [127, 129, 131, 133, 134, 144–146] is of the most critical challenges in this field. Aggregating the LCSA pillars is a complex issue [1, 122, 126, 129, 136, 140–142] due to the challenges associated with selecting the suitable indicators [3, 122, 125, 127–129, 145], weighting [1, 44, 126, 134, 139, 146–148], normalization [44, 134, 142, 146, 148], and formulating life cycle sustainability [1, 129, 130, 133, 139, 149, 150].

As illustrated in Fig. 8, the associated challenges of measuring LCSA could be initially classified into six groups, including Data, Measuring methods, Aggregation, Indicator selection, Uncertainties, and Results. Further and future research works need to be conducted to resolve these challenges. Apart from the continuous efforts to standardize the measuring methods, to develop databases and reduce the uncertainty of the evaluations through methodological advancements, new trends in the literature are found to answer the challenges of integrating and facilitating LCSA

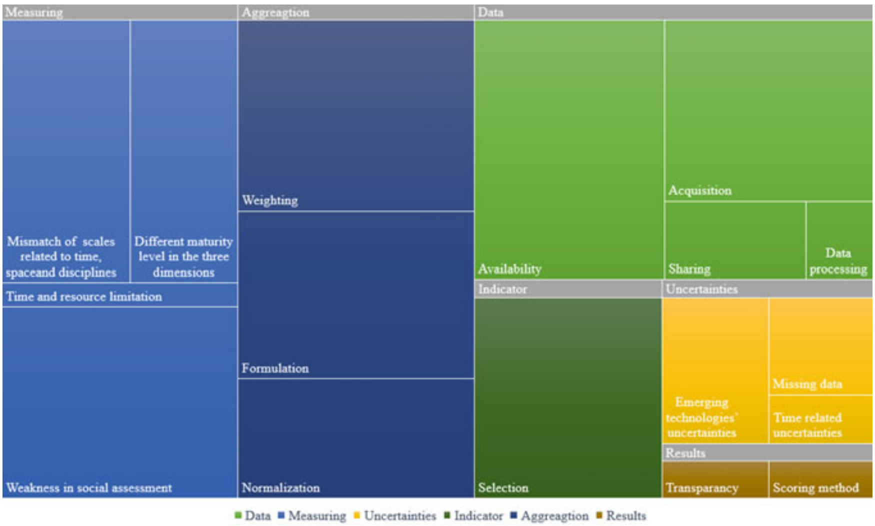

Fig. 8 Classification of the existing challenges related to measuring life cycle sustainability assessment. The size of each section corresponds with the number of papers addressed each challenge

in the building design process. The advent of developing integrated LCSA models and digitalization-LCSA nexus in the literature are examples of the new research trends aiming at providing solutions to ease the LCSA implementation in building and energy retrofitting design.

6.1 Integrated LCSA Models—Multi-dimensional LCSA Studies and Application of Optimization Methods

The research works that have addressed more than one LCSA dimension have constantly been increasing over the last few years. Several authors have included LCA and LCC simultaneously in their analysis, such as Krarti and Dubey [151] evaluated the economic and environmental benefits of three levels of energy retrofitting for different building types, including residential, commercial, and governmental buildings. Ruparathna et al. [152] proposed a method to find the best energy retrofit scenarios of buildings by considering energy consumption, life cycle costs, and GHG emission. Some researchers proposed a conceptual framework for an integrated LCSA model using a weighted-sum approach that includes all three LCSA pillars [153, 154]. Implementing LCSA into energy building energy retrofitting is a multi-objective task for which optimization methods and algorithms to find the extremum values of multi-variable functions are used by several authors over the last years to resolve the complexity of this task [1, 155].

Table 3 summarizes the recent research papers that addressed more than one LCSA pillar and represents the indicators and optimization algorithms adopted in each study.

Although several research papers have already been published addressing multi-dimensional life cycle sustainability assessment of buildings, our review showed that there are still challenges to be resolved. For instance, the lack of well-established quantification methods to measure SLCA is still a barrier to implement LCSA. Moreover, the lack of consensus on weighting methods for aggregating LCSA pillars is still an open challenge in this field. These challenges are expected to be resolved through future research on integration methods; however, it requires the development of LCI databases, measurement development, and standardization of LCSA pillars.

6.2 BIM-Based LCSA—A Solution for Data Management and Processing

Digitalization in the built environment and the application Building Information Modeling (BIM) are growing rapidly in the construction industry and can help

Table 3 Summary of integrated multidimensional LCSA studies

Author	LCA	LCC	SLCA	Indicators	Optimization algorithm
Chantrelle et al. [156]	✓	✓	✓	GC, Energy, CO_2, Thermal comfort	Genetic Algorithm: NSGA-II
Kusar et al. [118]	✗	✓	✓	NPV, Human live risk, Structural safety	✗
Risholt et al. [157]	✓	✓	✓	GC, CO_2,Thermal/ air quality	✗
Gustafsson et al. [158]	✓	✓	✗	GC, PEC, NRE, CO_2	✗
Holopainen et al. [119]	✓	✓	✓	GC, GWP, Social feasibility	✗
Pal et al. [159]	✓	✓	✗	Life cycle carbon footprint and life cycle cost	Genetic Algorithm: NSGA-II
Ramin et al. [160]	✓	✓	✓	Energy, CO_2, cost, water	Multi-objective optimization
Moschetti and Brattebø [161]	✓	✓	✗	NPV, CED, GWP	–
Ylmén et al. [162]	✓	✓	✗	Global warming potential, life cycle costs	Genetic Algorithm
M. Gustafsson et al. [163]	✓	✓	✗	NPV, GWP, Freshwater EP, particulate matter formation, NRPE	✗
Mauro et al. [164]	✗	✓	✓	LCC, Thermal comfort	NSGA-II algorithm
Mostavi et al. [117]	✓	✓	✓	LCE, LCC and Thermal comfort index	HS Algorithm
Almeida and Ferreira [165]	✓	✓	✗	GC, CO_2, PE	✗
Almeida [166]	✓	✓	✗	GC, GWP, NRPE, TPE	
Jokisalo et al. [167]	✓	✓	✗	LCC and Energy consumption	NSGA-II algorithm
Amirhosain and Hamma [168]	✓	✓	✗	LCC, energy consumption	NSGA-II algorithm, ANN, ML
Hirvonen et al. [169]	✓	✓	✗	LCC, CO_2 emission	NSGA-II algorithm
Conci et al. [170]	✓	✓	✗	NPV, GWP	✗
Amini Toosi and Lavagna [154]	✓	✓	✓	NPV, several environmental impacts, Thermal comfort	Genetic Algorithm

(continued)

Table 3 (continued)

Author	LCA	LCC	SLCA	Indicators	Optimization algorithm
Mateus et al. [171]	✓	✓	✗	NPV, GWP, CED	✗

and support the integrated design process through improving information management and cooperation between designers, producers, and end-users during the whole buildings' life cycle stages [172–175].

Buildings consist of various components; this brings a massive amount of information and complexity to the design phase [176]. This is usually reported as the main reason for performing LCSA at the later project phases, where the complexity and uncertainties are reduced [177, 178]. BIM tools are capable of providing and present both graphical, numerical, and descriptive information of buildings in different levels of development (LOD) [179–182], which is an important requirement for applying an LCA during the design phase. It is also reported that the use of LCA methods in the building sector cannot be developed without developing the level of information in this sector, on the other hand, it is stated that the use of BIM for public buildings will be compulsory in the EU from October 2018 [182] and expected to be extensively used in the near future [173]. All these facts indicate that BIM-based life cycle sustainability assessment is a promising and indispensable solution to resolving data integration and management challenges.

Several researchers have addressed the application of BIM in building life cycle assessment. For instance, Malmqvist et al. [183] proposed BIM tools to overcome data analysis problems during the early stages of the design process. They indicated that in the early stages of design, there are many possible solutions and decisions to take, while the precise data which are required for the LCA calculations are usually available at the later design stages. To overcome this problem, speed up the LCA calculation process, and increase the accuracy and completeness of the evaluations, they suggested using BIM tools in the LCA-design process [183].

Many researchers have elaborated the necessity of BIM application in LCA and have tried to use BIM tools in an LCA process [181, 184–187]. Although many studies demonstrate the advantages and benefits of BIM-based life cycle assessment and the integration of BIM and LCA [187–189], serious challenges such as software integration or data requirements are still the main problems and barriers in this field [182]. The existing BIM tools are not capable of comparing different alternatives, also still suffer from data library limitations [74, 184, 186]. It is understandable that in order to make the BIM-LCA integration useful, the input data, assessment process, result acquisition, and interpretation must be as easily achievable as soon as possible, and the whole integrated assessment system must be user-friendly [182].

The integration between BIM tools and energy simulation software is not still fully developed. Also, data exchange between BIM and LCA tools is another critical issue. In some research works, automated produced bills of materials are imported into the excel sheets for the LCA calculation. Ajayi et al. [187], Basbagill et al.

[190], Peng [184], and Houlihan et al. [191], as well as many other researchers, have used a manual process for data exchange between BIM tools and LCA tools or LCA calculation sheet in Excel. However, some plugins on Revit Autodesk make it possible to quantify environmental impacts in the BIM environment based on LCA methods [183, 193]. There is still a gap in software integration between BIM, LCSA, and energy simulation tools.

Another problem stated and confirmed by researchers is that BIM databases are not developed enough for the LCA process. Because of this problem, in most cases, the bill of material quantities and material properties are edited manually by the end-users [182].

Although the BIM concept is not effective in integrating building performance assessment into the sketch design phase due to the excessive required time for modeling [192], if the task is about implementing the LCSA in designing energy retrofit scenarios, BIM can significantly facilitate the assessment process, since many of design parameters have already been defined and the uncertainty is lower in energy retrofit design compared to the sketch and initial design phase.

To start an integrated BIM-LCSA design process, some questions must be answered first:

1. What are the design and assessment goals? The answer will determine what kinds of performance criteria must be assessed.
2. What is the assessment methodology, and what kind of assessment methodologies need to be integrated into BIM?
3. What kind of data and databases need to be integrated into BIM?
4. What is the required detail, accuracy, and completeness level for the performance assessment?
5. How should the result be reported, and in which way should they be processed and used?

As an example to answer one of these questions, Dupuis et al. [193] indicated that to be able to perform an accurate LCA study and achieve sound results, every data element should be at least at the LOD 350 detail level. Each BIM model at a lower level than LOD 350 means that some essential data for LCA calculation will be missed.

Although BIM-based LCSA is a promising solution to overcome the integration challenges of LCSA in building and energy retrofit design, there are still some challenges in applying this framework, such as availability of life cycle inventory (LCI) databases, software integration, and transferring building information between modeling software and LCSA tools. Given the rapid progress in developing design-assessment tools and LCI databases, it is expected that LCSA analyses would be possible to be performed in the BIM environment without using intermediary tools in the near future.

7 Conclusion

This chapter discussed how sustainability assessment has been developed from a single-dimension and environmental-oriented interpretation to a multidimensional interdisciplinary research field by reviewing its roots and evolution path over the last decades. Then we discussed how decision-making models have been integrated into life cycle sustainability assessment of buildings to facilitate the informed decision-making in the multi-objective design-assessment contexts such as building life cycle assessment. Through literature review on the implementation of LCSA in building energy retrofitting, we discussed the existing challenges of the life cycle sustainability assessment. We concluded that different assumptions such as various functional units, system boundaries, and lack of a wide range of standard environmental impacts result in complexities in the comparability of the reviewed research works. Moreover, the lack of LCI databases is known as the main obstacle of LCA application. Also, we showed that the level of documentation of some research works is lower than the recommendation by relevant standards, which need to be considered in future research works to enhance the readability and comparability of the results.

Regarding the LCC studies, we showed that Net Present Value is the most popular economic indicator used by several researchers to evaluate the economic performance of their retrofit design. Macroeconomic parameters such as discount rate and energy price inflation rate adopted in each paper were discussed, and we showed that the assumed values in the research papers are lower than the actual values in the economic context of the study in most cases. However, we highlighted that several papers have taken various values of discount rate and energy price inflation rate to evaluate the impacts of these parameters on the final results.

In this review, the lack of integrating social life cycle assessment into evaluating energy retrofit design is found as one of the main limitations. The SLCA is less developed than LCA and LCC and requires more methodological advancements, especially in developing measurement methods, quantifiable indicators, and databases.

It is also found that the number of multidimensional LCSA studies in building and energy retrofit design is increasing over the preceding years, and several researchers have proposed integrated frameworks to implement LCSA into the building design. In this context, the development of optimization algorithms and available tools are promising solutions to facilitate the LCSA implementation in the multi-objective building design process. Likewise, the BIM-based approach to integrate LCSA into the building design process attracted the researcher's attention for solving the complexity of data management and processing in building life cycle sustainability assessment. Nevertheless, it is essential to develop measurement methods, standardization, and aggregation methods of LCSA pillars alongside providing more comprehensive databases and developing integrated software and tools by future research works to facilitate the implementation of LCSA in the building and energy retrofit design process.

References

1. Amini Toosi H, Lavagna M, Leonforte F, Del Pero C, Aste N (2020) Life cycle sustainability assessment in building energy retrofitting—a review. Sustain Cities Soc 60:102248, Sep. 01, 2020. Elsevier Ltd. https://doi.org/10.1016/j.scs.2020.102248
2. Du Pisani JA (2006) Sustainable development—historical roots of the concept. Environ Sci 3(2):83–96. https://doi.org/10.1080/15693430600688831
3. Komeily A, Srinivasan RS (2015) A need for balanced approach to neighborhood sustainability assessments: a critical review and analysis. Sustain Cities Soc 18:32–43. https://doi.org/10.1016/j.scs.2015.05.004
4. Clark WC, Dickson NM (2003) Sustainability science: the emerging research program. Proc Natl Acad Sci 100(14):8059–8061. https://doi.org/10.1073/pnas.1231333100
5. Mensah J (2019) Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. Cogent Soc Sci 5(1). https://doi.org/10.1080/23311886.2019.1653531
6. Aste N, Caputo P, Buzzetti M, Fattore M (2016) Energy efficiency in buildings: what drives the investments? the case of lombardy region. Sustain Cities Soc 20:27–37. https://doi.org/10.1016/J.SCS.2015.09.003
7. Mirabella N et al (2018) Strategies to Improve the energy performance of buildings: a review of their life cycle impact. Buildings 8(8):105. https://doi.org/10.3390/buildings8080105
8. Song K, Ahn Y, Ahn J, Kwon N (2019) Development of an energy saving strategy model for retrofitting existing buildings: a Korean case study. Energies 12(9). https://doi.org/10.3390/en12091626
9. Mebratu D (1998) Sustainability and sustainable development: historical and conceptual review. Environ Impact Assess Rev 18(6):493–520. https://doi.org/10.1016/S0195-9255(98)00019-5
10. Roostaie S, Nawari N, Kibert CJ (2019) Sustainability and resilience : a review of definitions, relationships, and their integration into a combined building assessment framework. Build Environ 154(March):132–144. https://doi.org/10.1016/j.buildenv.2019.02.042
11. Hartwick JM (1974) Price sustainability of location assignments. J Urban Econ 1(2):147–160. https://doi.org/10.1016/0094-1190(74)90014-X
12. Shi L, Han L, Yang F, Gao L (2019) The evolution of sustainable development theory: types, goals, and research prospects. Sustain 11(24):1–16. https://doi.org/10.3390/su11247158
13. Development (2020) "Development," Oxford online dictionary. https://www.oxfordlearnersdictionaries.com/definition/english/development
14. UN (1972) United Nations conference on the human environment (Stockholm Conference). United Nation. https://sustainabledevelopment.un.org/milestones/humanenvironment
15. United_Nations (1972) Report of the United Nations Conference on the Human Environment. New York
16. Our_Common_Future (1987) Report of the world commission on environment and development: our common future. New York
17. UN (1992) United Nations Conference on Environment and Development (UNCED), Earth Summit (Rio de Janeiro, Brazil). https://sustainabledevelopment.un.org/milestones/unced
18. Rio_Conference (1992) Report of the united nations conference on environment and development. New York
19. Johannesburg_Conference (2002). Report of the World Summit on Sustainable Development (WSSD), Johannesburg Summit. New York
20. UN (2012) United Nations Conference on Sustainable Development, Rio+20. https://sustainabledevelopment.un.org/rio20
21. Rio+20 (2012) Resolution adopted by the General Assembly on 27 July 2012, (The future we want). New York
22. UN (2013) Millennium Development Goals (MDGs). https://www.un.org/millenniumgoals/bkgd.shtml

23. UNSDS (2015) Resolution adopted by the General Assembly on 25 September 2015, Transforming our world: the 2030 Agenda for Sustainable Development. New York
24. UN (2015) The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
25. Mattoni B, Guattari C, Evangelisti L, Bisegna F, Gori P, Asdrubali F (2018) Critical review and methodological approach to evaluate the differences among international green building rating tools. Renew Sustain Energy Rev 82(October 2017):950–960. https://doi.org/10.1016/j.rser.2017.09.105
26. Lim YS et al (2015) Education for sustainability in construction management curricula. Int J Constr Manag 15(4):321–331. https://doi.org/10.1080/15623599.2015.1066569
27. UNEP (2018) Global alliance for buildings and construction, 2018 global status report, p 325. https://doi.org/10.1038/s41370-017-0014-9
28. Mateus R, Silva SM, De Almeida MG (2019) Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings. Renew Energy 137:82–92. https://doi.org/10.1016/j.renene.2018.04.036
29. Janjua SY, Sarker PK, Biswas WK (2020) Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings, 264(November 2019)
30. United Nations Environmental Program (UNEP) (2011) Note 12: Towards a L ife C ycle S ustainability A ssessment
31. Kamali M, Hewage K, Milani AS (2018) Life cycle sustainability performance assessment framework for residential modular buildings: aggregated sustainability indices. Build Environ 138(March):21–41. https://doi.org/10.1016/j.buildenv.2018.04.019
32. Doan DT, Ghaffarianhoseini A, Naismith N, Zhang T, Ghaffarianhoseini A, Tookey J (2017) A critical comparison of green building rating systems. Build Environ 123:243–260. https://doi.org/10.1016/j.buildenv.2017.07.007
33. Visentin C, William A, Braun AB (2020) Life cycle sustainability assessment : a systematic literature review through the application perspective , indicators, and methodologies 270. https://doi.org/10.1016/j.jclepro.2020.122509
34. Lippiatt B (2007) BEES 4.0: Building for environmental and economic sustainability, technical manual and user guide, director, p. 307, 2007, doi: 860108
35. CEN/TC-350 CEN/TC-350 (European Committee for Standardization (CEN)) (2010) EN 15643-1:2010, Sustainability of construction works—sustainability assessment of buildings—Part 1: General framework
36. CEN/TC-350 CEN/TC-350 (European Committee for Standardization (CEN)) (2011) EN 15643-2:2011 Sustainability of construction works—assessment of buildings—Part 2: Framework for the assessment of environmental performance
37. CEN/TC-350 CEN/TC-350 (European Committee for Standardization (CEN)) (2012) EN 15643-3:2012 Sustainability of construction works—assessment of buildings—Part 3: Framework for the assessment of social performance
38. CEN/TC-350 (European Committee for Standardization (CEN)), "EN 15643-4:2012 Sustainability of construction works - Assessment of buildings - Part 4: Framework for the assessment of economic performance," 2012.
39. EN_15978 (2011) EN 15978:2011, Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method
40. EN_16627 (2015) EN 16627:2015 Sustainability of construction works. Assessment of economic performance of buildings. Calculation methods
41. EN_16309:2014+A1:2014 (2014) EN 16309:2014+A1:2014, Sustainability of construction works. Assessment of social performance of buildings. Calc Methodol
42. Valentin A, Spangenberg JH (2000) A guide to community sustainability indicators 20:381–392
43. Shari A, Murayama A (2014) Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US , the UK, and Japan," vol 72. https://doi.org/10.1016/j.buildenv.2013.11.006

44. Sala S, Farioli F, Zamagni A (2013) Life cycle sustainability assessment in the context of sustainability science progress (part 2), pp 1686–1697. https://doi.org/10.1007/s11367-012-0509-5
45. Frankel J (1959) Towards a decision-making model in foreign polICY. Polit Stud 7(1):1–11. https://doi.org/10.1111/j.1467-9248.1959.tb00888.x
46. Reynolds PA (1959) A comment on Mr. Frankel's article towards a decision-making model in foreign policy. Polit Stud 7(3):302–304
47. Gong B, Liu R, Zhang X (2020) Market acceptability assessment of electric vehicles based on an improved stochastic multicriteria acceptability analysis-evidential reasoning approach. J Clean Prod 269:121990.https://doi.org/10.1016/j.jclepro.2020.121990
48. Medineckiene M, Zavadskas EK, Björk F, Turskis Z (2015) Multi-criteria decision-making system for sustainable building assessment/certification. Arch Civ Mech Eng 15(1):11–18. https://doi.org/10.1016/j.acme.2014.09.001
49. VillarinhoRosa L, Haddad AN (2013) Building Sustainability Assessment throughout Multicriteria Decision Making. J Constr Eng 2013:1–9. https://doi.org/10.1155/2013/578671
50. Karjalainen TP et al (2013) A decision analysis framework for stakeholder involvement and learning in groundwater management. Hydrol Earth Syst Sci 17(12):5141–5153. https://doi.org/10.5194/hess-17-5141-2013
51. Hannouf M, Assefa G (2018) A life cycle sustainability assessment-based decision-analysis framework. Sustain 10(11). https://doi.org/10.3390/su10113863
52. Aspegren G, Hellström H, Olsson B (1997) The urban water system—a future Swedish perspective. Water Sci Technol 35(9):33–43.https://doi.org/10.1016/S0273-1223(97)00182-0
53. Diaz-balteiro L, González-pachón J, Romero C (2017) Measuring systems sustainability with multi-criteria methods: a critical review. Eur J Oper Res 258(2):607–616.https://doi.org/10.1016/j.ejor.2016.08.075
54. Zarte M, Pechmann A, Nunes IL (2019) Decision support systems for sustainable manufacturing surrounding the product and production life cycle e A literature review. J Clean Prod 219:336–349. https://doi.org/10.1016/j.jclepro.2019.02.092
55. Siksnelyte I, Zavadskas EK, Streimikiene D, Sharma D (2018) An overview of multi-criteria decision-making methods in dealing with sustainable energy development issues. Energies 11(10). https://doi.org/10.3390/en11102754
56. Chandrakumar C, Kulatunga A, Mathavan S (2018) A multi-criteria decision-making model to evaluate sustainable product designs based on the principles of Design for Sustainability and Fuzzy Analytic Hierarchy Process A multi-criteria decision-making model to evaluate sustainable product designs based o. Sustain Des Manuf 2017. SDM 2017. Smart Innov. Syst. Technol. Springer, Cham, vol 68, no June, pp 347–354, 2018, doi: https://doi.org/10.1007/978-3-319-57078-5_34
57. Bakhoum ES, Brown DC (2013) A hybrid approach using AHP-TOPSIS—entropy methods for sustainable ranking of structural materials. Int J Sustain Eng Taylor Fr 6(3):212–224. https://doi.org/10.1080/19397038.2012.719553
58. Saaty TL (1980) The analytical hierarchical process. Wiley, New York
59. Saaty TL (2008) Decision making with the analytic hierarchy process, 1(1)
60. Walling E (2020) Developing successful environmental decision support systems: challenges and best practices 264 no(April, 2020). https://doi.org/10.1016/j.jenvman.2020.110513.
61. Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol Indic 46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011
62. Liu S, Qian S (2019) Towards sustainability—oriented decision making : Model development and its validation via a comparative case study on building construction methods, no. June 2018, pp 860–872, 2019. https://doi.org/10.1002/sd.1946
63. Alireza Ahmadian FF, Rashidi TH, Akbarnezhad A, Waller ST (2015) BIM-enabled sustainability assessment of material supply decisions. doi: https://doi.org/10.1108/ECAM-12-2015-0193

64. Arroyo P, Tommelein ID, Ballard G, Rumsey P (2015) Choosing by advantages: a case study for selecting an HVAC system for a net zero energy museum Choosing by advantages: a case study for selecting an HVAC system for a net zero energy museum. Energy Build 111(October):26–36. https://doi.org/10.1016/j.enbuild.2015.10.023
65. Medineckiene M, Monitoring HE, Centre A, Turskis Z, Zavadskas EK (2011) Life-cycle analysis of a sustainable building , aplying multi-criteria decision making method, no. October 2014
66. Wang N, Chang Y, Nunn C (2010) Lifecycle assessment for sustainable design options of a commercial building in Shanghai. Build Environ 45(6):1415–1421. https://doi.org/10.1016/j.buildenv.2009.12.004
67. Hwang K, Yoon CL (1981) Multiple attribute decisionmaking: methods and applications. Springer, New York
68. Velasquez M, Hester P (2013) An analysis of multi-criteria decision making methods. Int J Oper Res 10(2):56–66
69. Anand CK, Amor B (2017) Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 67:408–416. https://doi.org/10.1016/j.rser.2016.09.058
70. Assiego de Larriva R, Calleja Rodríguez G, Cejudo López JM, Raugei M, Fullana i Palmer P (2014) A decision-making LCA for energy refurbishment of buildings: Conditions of comfort. Energy Build 70:333–342. https://doi.org/10.1016/J.ENBUILD.2013.11.049
71. García-Pérez S, Sierra-Pérez J, Boschmonart-Rives J (2018) Environmental assessment at the urban level combining LCA-GIS methodologies: a case study of energy retrofits in the Barcelona metropolitan area. Build Environ 134:191–204. https://doi.org/10.1016/J.BUILDENV.2018.01.041
72. Ghose A, McLaren SJ, Dowdell D, Phipps R (2017) Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. Build Environ, 117:274–287, May 2017, Accessed: Dec. 05, 2018. https://www.sciencedirect.com/science/article/pii/S0360132317301105
73. Beccali M, Cellura M, Fontana M, Longo S, Mistretta M (2013) Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. Renew Sustain Energy Rev 27:283–293. https://doi.org/10.1016/j.rser.2013.05.040
74. Anand CK, Amor B (2017) Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 67:408–416. https://doi.org/10.1016/j.rser.2016.09.058
75. Bin G, Parker P (2012) Measuring buildings for sustainability: comparing the initial and retrofit ecological footprint of a century home—the REEP House. Appl Energy 93:24–32. https://doi.org/10.1016/j.apenergy.2011.05.055
76. Mangan SD, Koçlar Oral G (2016) Life cycle assessment of energy retrofit strategies for an existing residential building in Turkey. A/Z ITU J Fac Archit 13(2):143–156. https://doi.org/10.5505/itujfa.2016.26928
77. Valančius K, Vilutienė T, Rogoža A (2018) Analysis of the payback of primary energy and CO_2 emissions in relation to the increase of thermal resistance of a building. Energy Build. 179:39–48. https://doi.org/10.1016/J.ENBUILD.2018.08.037
78. Mangan SD, Oral GK (2015) A study on life cycle assessment of energy retrofit strategies for residential buildings in Turkey. Energy Procedia 78:842–847. https://doi.org/10.1016/J.EGYPRO.2015.11.005
79. Marique A-F, Rossi B (2018) Cradle-to-grave life-cycle assessment within the built environment: comparison between the refurbishment and the complete reconstruction of an office building in Belgium. J Environ Manage 224:396–405. https://doi.org/10.1016/J.JENVMAN.2018.02.055
80. Oregi X, Hernandez P, Hernandez R (2017) Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects. Energy Build. 136:12–25. https://doi.org/10.1016/j.enbuild.2016.11.057

81. Nydahl H, Andersson S, Åstrand A, Olofsson T (2019) Environmental performance measures to assess building refurbishment from a life cycle perspective. Energies 12(2):299. https://doi.org/10.3390/en12020299
82. Oregi X, Hernandez P, Gazulla C, Isasa M (2015) Integrating simplified and full life cycle approaches in decision making for building energy refurbishment: benefits and barriers. Buildings 5(2):354–380. https://doi.org/10.3390/buildings5020354
83. Tadeu S, Rodrigues C, Tadeu A, Freire F, Simões N (2015) Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. J Build Eng 4:167–176. https://doi.org/10.1016/J.JOBE.2015.09.009
84. Ouyang J, Lu M, Li B, Wang C, Hokao K (2011) Economic analysis of upgrading aging residential buildings in China based on dynamic energy consumption and energy price in a market economy. Energy Policy 39(9):4902–4910. https://doi.org/10.1016/J.ENPOL.2011.06.025
85. Toosi HA, Balador Z, Gjerde M, Vakili-Ardebili A (2018) A life cycle cost analysis and environmental assessment on the photovoltaic system in buildings: two case studies in Iran. J Clean Energy Technol 6(2):134–138. https://doi.org/10.18178/jocet.2018.6.2.448
86. Jafari A, Valentin V, Russell M (2016) Sensitivity analysis of factors affecting decision-making for a housing energy retrofit: a case study, no. May 2016, pp 1254–1263. https://doi.org/10.1061/9780784479827.126
87. Copiello S, Gabrielli L, Bonifaci P (2017) Evaluation of energy retrofit in buildings under conditions of uncertainty: the prominence of the discount rate. Energy 137:104–117. https://doi.org/10.1016/j.energy.2017.06.159
88. Lucchi E, Tabak M, Troi A (2017) The 'cost optimality' approach for the internal insulation of historic buildings. Energy Procedia 133:412–423. https://doi.org/10.1016/J.EGYPRO.2017.09.372
89. Yuan J, Nian V, Su B (2019) Evaluation of cost-effective building retrofit strategies through soft-linking a metamodel-based Bayesian method and a life cycle cost assessment method. Appl Energy 253: 113573, 2019. https://doi.org/10.1016/j.apenergy.2019.113573
90. Liu L, Rohdin P, Moshfegh B (2016) LCC assessments and environmental impacts on the energy renovation of a multi-family building from the 1890s. Energy Build. 133:823–833. https://doi.org/10.1016/J.ENBUILD.2016.10.040
91. Copiello S, Gabrielli L, Bonifaci P (2017) Evaluation of energy retrofit in buildings under conditions of uncertainty: the prominence of the discount rate. Energy 137:104–117, Oct. 2017. https://doi.org/10.1016/J.ENERGY.2017.06.159
92. Bleyl JW et al (2019) Office building deep energy retrofit: life cycle cost benefit analyses using cash flow analysis and multiple benefits on project level. Energy Effic 12(1):261–279. https://doi.org/10.1007/s12053-018-9707-8
93. Van De Moortel E et al (2019) Energy Renovation of Social Housing : Finding a Balance Between Increasing Insulation and Improving Heating System Efficiency Energy Renovation of Social Housing : Finding a Balance Between Increasing Insulation and Improving Heating System Efficiency," IOP Conf. Ser. Earth Environ Sci Cent Eur Towar Sustain Build. doi: https://doi.org/10.1088/1755-1315/290/1/012137
94. Ruparathna R, Hewage K, Sadiq R (2017) Economic evaluation of building energy retrofits: a fuzzy based approach. Energy Build. 139:395–406. https://doi.org/10.1016/j.enbuild.2017.01.031
95. Zheng D, Yu L, Wang L, Tao J (2019) A screening methodology for building multiple energy retrofit measures package considering economic and risk aspects. J Clean Prod 208:1587–1602. https://doi.org/10.1016/J.JCLEPRO.2018.10.196
96. Lohse R, Staller H, Riel M (2016) The economic challenges of deep energy renovation—differences, similarities, and possible solutions in central Europe: Austria and Germany. ASHRAE Conf. 122:69–87
97. Fregonara E, Lo Verso VRM, Lisa M, Callegari G (2017) Retrofit scenarios and economic sustainability. A case-study in the italian context. Energy Procedia, vol. 111, pp. 245–255, Mar. 2017, doi: https://doi.org/10.1016/J.EGYPRO.2017.03.026.

98. D'Orazio M, Di Giuseppe E, Esposti R, Coderoni S, Baldoni E (2018) A probabilistic tool for evaluating the effectiveness of financial measures to support the energy improvements of existing buildings.In: IOP Conf. Ser. Mater. Sci. Eng., vol 415, p 012003, Nov. 2018https://doi.org/10.1088/1757-899X/415/1/012003
99. Seghezzi R-CE, Masera G (2019) Decision Support for existing buildings : an LCC-based proposal for facade retrofitting technological choices Decision Support for existing buildings : an LCC-based proposal for facade retrofitting technological choices. In: IOP Conf. Ser. Earth Environ Sci 296, 2019, doi: https://doi.org/10.1088/1755-1315/296/1/012032
100. Krarti M, Dubey K (2017) Energy productivity evaluation of large scale building energy efficiency programs for Oman. Sustain Cities Soc 29:12–22. https://doi.org/10.1016/J.SCS.2016.11.009
101. Brás A, Rocha A, Faustino P (2015) Integrated approach for school buildings rehabilitation in a Portuguese city and analysis of suitable third party financing solutions in EU. J. Build. Eng. 3:79–93. https://doi.org/10.1016/J.JOBE.2015.05.003
102. Gustafsson S-I, Karlsson BG (1989) Insulation and bivalent heating system optimization: Residential housing retrofits and time-of-use tariffs for electricity. Appl Energy 34(4):303–315. https://doi.org/10.1016/0306-2619(89)90035-4
103. S. Gustafsson, "Energy conservation and optimal retrofits in multifamily buildings," Energy Syst. Policy, ISSN 0090–8347, Vol. 14, p. 37–49, pp. 1–13, 1990.
104. Gustafsson S-I, Karlsson BG (1991) Window retrofits: Interaction and life-cycle costing. Appl Energy 39(1):21–29. https://doi.org/10.1016/0306-2619(91)90060-B
105. Gustafsson S-I, Andersson S, Karlsson BG (1994) Factorial design for energy-system models. Energy 19(8):905–910. https://doi.org/10.1016/0360-5442(94)90043-4
106. Gustafsson S-I (1998) Sensitivity analysis of building energy retrofits. Appl Energy 61(1):13–23. https://doi.org/10.1016/S0306-2619(98)00032-4
107. V. Mili, K. Ekelöw, and B. Moshfegh, "On the performance of LCC optimization software OPERA-MILP by comparison with building energy simulation software IDA ICE," vol. 128, no. July 2017, pp. 305–319, 2018, doi: https://doi.org/10.1016/j.buildenv.2017.11.012.
108. C. Nägeli, A. Farahani, M. Österbring, J. Dalenbäck, and H. Wallbaum, "A service-life cycle approach to maintenance and energy retrofit planning for building portfolios," Build. Environ., vol. 160, no. June, p. 106212, 2019, doi: https://doi.org/10.1016/j.buildenv.2019.106212.
109. La Fleur L, Rohdin P, Moshfegh B (2019) Energy Renovation versus Demolition and Construction of a New Building — A Comparative Analysis of a Swedish Multi-Family Building. Energies 12:12–15. https://doi.org/10.3390/en12112218
110. Koo C, Kim H, Hong T (2014) Framework for the analysis of the low-carbon scenario 2020 to achieve the national carbon Emissions reduction target: Focused on educational facilities. Energy Policy 73:356–367. https://doi.org/10.1016/j.enpol.2014.05.009
111. Koo C, Hong T, Kim J, Kim H (2015) An integrated multi-objective optimization model for establishing the low-carbon scenario 2020 to achieve the national carbon emissions reduction target for residential buildings. Renew Sustain Energy Rev 49:410–425. https://doi.org/10.1016/J.RSER.2015.04.120
112. S. D. Mangan and G. Koçlar Oral, "A study on determining the optimal energy retrofit strategies for an existing residential building in Turkey," A/Z ITU J. Fac. Archit., vol. 11, no. 2, pp. 307–333, 2014.
113. E. S. Umdu, "Methodological approach for performance assessment of historical buildings based on seismic , energy and cost performance : A Mediterranean," J. Build. Eng., vol. 31, no. March, 2020, doi: https://doi.org/10.1016/j.jobe.2020.101372.
114. Y. Yılmaz and G. Koçlar Oral, "An approach for an educational building stock energy retrofits through life-cycle cost optimization," Archit. Sci. Rev., vol. 61, no. 3, pp. 122–132, May 2018, doi: https://doi.org/10.1080/00038628.2018.1447438.
115. Jafari A, Valentin V (2015) Decision-making life-cycle cost analysis model for energy-efficient housing retrofits. Int J Sustain Build Technol Urban Dev 6(3):173–187. https://doi.org/10.1080/2093761X.2015.1074948

116. A. Jafari and V. Valentin, “An Investment Allocation Approach for Building Energy Retrofits,” no. May 2016, pp. 1061–1070, 2016, doi: https://doi.org/10.1061/9780784479827.107.
117. Mostavi E, Asadi S, Boussaa D (2017) Development of a new methodology to optimize building life cycle cost, environmental impacts, and occupant satisfaction. Energy 121:606–615. https://doi.org/10.1016/J.ENERGY.2017.01.049
118. Kušar M, Šubic M, Šelih J (2013) Selection of Efficient Retrofit Scenarios for Public Buildings. Procedia Eng. 57:651–656. https://doi.org/10.1016/j.proeng.2013.04.082
119. Holopainen R, Milandru A, Ahvenniemi H, Häkkinen T (2016) Feasibility Studies of Energy Retrofits – Case Studies of Nearly Zero-energy Building Renovation. Energy Procedia 96:146–157. https://doi.org/10.1016/J.EGYPRO.2016.09.116
120. Assiego de Larriva R, Calleja Rodríguez G, Cejudo López JM, Raugei M, Fullana i Palmer P (2014) A decision-making LCA for energy refurbishment of buildings: conditions of comfort,” Energy Build 70:333–342, Feb. 2014. https://doi.org/10.1016/J.ENBUILD.2013.11.049
121. Sala S, Farioli F, Zamagni A (2013) Progress in sustainability science : lessons learnt from current methodologies for sustainability assessment : Part 1,” pp 1653–1672. https://doi.org/10.1007/s11367-012-0508-6.
122. C. Llatas, B. Soust-verdaguer, and A. Passer, “Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling : From systematic literature review to a methodological approach,” Build. Environ., vol. 182, no. July, p. 107164, 2020, doi: https://doi.org/10.1016/j.buildenv.2020.107164.
123. Messerli P et al (2019) Expansion of sustainability science needed for the SDGs. Nat. Sustain. 2(10):892–894. https://doi.org/10.1038/s41893-019-0394-z
124. Pauliuk S (2020) Making sustainability science a cumulative effort. Nat. Sustain. 3(1):2–4. https://doi.org/10.1038/s41893-019-0443-7
125. J. Fariña-tojo and J. Rajaniemi, Urban Ecology, Emerging Patterns and Social-Ecological Systems, (Chapter 19 - Challenges in assessing urban sustainability), no. July. Elsevier Inc., 2020.
126. Sala S, Ciuffo B, Nijkamp P (2015) A systemic framework for sustainability assessment. Ecol Econ 119:314–325. https://doi.org/10.1016/j.ecolecon.2015.09.015
127. A. Zamagni, H. Pesonen, and T. Swarr, “From LCA to Life Cycle Sustainability Assessment : concept , practice and future directions,” pp. 1637–1641, 2013, doi: https://doi.org/10.1007/s11367-013-0648-3.
128. A. Lehmann, E. Zschieschang, and M. Traverso, “Social aspects for sustainability assessment of technologies — challenges for social life cycle assessment (SLCA),” pp. 1581–1592, 2013, doi: https://doi.org/10.1007/s11367-013-0594-0.
129. I. Huertas-valdivia, A. M. Ferrari, D. Settembre-blundo, and F. E. Garc, “Social Life-Cycle Assessment : A Review by Bibliometric Analysis,” pp. 1–25, 2020.
130. Contestabile M (2020) Measuring for sustainability. Nat. Sustain. 3(8):576. https://doi.org/10.1038/s41893-020-0570-1
131. D. S. Zachary, “On the sustainability of an activity,” Sci. Rep., vol. 4, 2014, doi: https://doi.org/10.1038/srep05215.
132. Moallemi EA et al (2020) Perspective Achieving the Sustainable Development Goals Requires Transdisciplinary Innovation at the Local Scale. One Earth 3(3):300–313. https://doi.org/10.1016/j.oneear.2020.08.006
133. O. Tokede and M. Traverso, “Implementing the guidelines for social life cycle assessment : past , present , and future,” pp. 1910–1929, 2020.
134. R. J. Bonilla-alicea and K. Fu, “Systematic Map of the Social Impact Assessment Field,” 2019.
135. Alexander SM et al (2020) Qualitative data sharing and synthesis for sustainability science. Nat. Sustain. 3(2):81–88. https://doi.org/10.1038/s41893-019-0434-8
136. A. Zamagni, “Life cycle sustainability assessment,” pp. 373–376, 2012, doi: https://doi.org/10.1007/s11367-012-0389-8.
137. Matthews NE, Stamford L, Shapira P (2019) Aligning sustainability assessment with responsible research and innovation : Towards a framework for Constructive Sustainability Assessment. Sustain. Prod. Consum. 20:58–73. https://doi.org/10.1016/j.spc.2019.05.002

138. J. Pedro, C. Silva, and M. Duarte, "Scaling up LEED-ND sustainability assessment from the neighborhood towards the city scale with the support of GIS modeling : Lisbon case study," Sustain. Cities Soc., vol. 41, no. May 2017, pp. 929–939, 2018, doi: https://doi.org/10.1016/j.scs.2017.09.015.
139. H. H. Dang and U. Serajuddin, "Tracking the sustainable development goals: Emerging measurement challenges and further reflections," World Dev., vol. 127, p. 104570, 2020https://doi.org/10.1016/j.worlddev.2019.05.024
140. R. Phillips, L. Troup, D. Fannon, and M. J. Eckelman, "Triple bottom line sustainability assessment of window-to-wall ratio in US office buildings," Build. Environ., vol. 182, no. January, p. 107057, 2020, doi: https://doi.org/10.1016/j.buildenv.2020.107057.
141. C. Galvão and W. Viegas, "Inquiry in higher education for sustainable development : crossing disciplinary knowledge boundaries," vol. 2020, 2020, doi: https://doi.org/10.1108/IJSHE-02-2020-0068.
142. S. Huysveld, S. E. Taelman, S. Sfez, and J. Dewulf, "A framework for using the handprint concept in attributional life cycle (sustainability) assessment," vol. 265, pp. 1–9, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.121743.
143. Partelow S (2016) Coevolving Ostrom ' s social – ecological systems (SES) framework and sustainability science : four key co-benefits. Sustain Sci 11(3):399–410. https://doi.org/10.1007/s11625-015-0351-3
144. L. Wan, E. Ng, L. Wan, and E. Ng, "Evaluation of the social dimension of sustainability in the built environment in poor rural areas of China Evaluation of the social dimension of sustainability in the built environment in poor rural areas of China," vol. 8628, 2018, doi: https://doi.org/10.1080/00038628.2018.1505595.
145. P. Verma and A. S. Raghubanshi, "Urban sustainability indicators : Challenges and opportunities," vol. 93, no. May, pp. 282–291, 2018, doi: https://doi.org/10.1016/j.ecolind.2018.05.007.
146. Andreas R, Serenella S, Jungbluth N (2020) Normalization and weighting: the open challenge in LCA. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-020-01790-0
147. N. Pelletier, N. Bamber, and M. Brandão, "Interpreting life cycle assessment results for integrated sustainability decision support : can an ecological economic perspective help us to connect the dots ?," pp. 1580–1586, 2019.
148. Pizzol M, Laurent A, Sala S, Weidema B, Verones F, Koffler C (2017) Normalisation and weighting in life cycle assessment: quo vadis? Int J Life Cycle Assess 22(6):853–866. https://doi.org/10.1007/s11367-016-1199-1
149. M. Abubakr, A. T. Abbas, I. Tomaz, M. S. Soliman, M. Luqman, and H. Hegab, "Sustainable and Smart Manufacturing : An Integrated Approach," 2020.
150. P. Halla, V. Superti, A. Boesch, and C. R. Binder, "Indicators for urban sustainability : Key lessons from a systematic analysis of 67 measurement initiatives," Ecol. Indic., vol. 119, no. April, p. 106879, 2020, doi: https://doi.org/10.1016/j.ecolind.2020.106879.
151. Krarti M, Dubey K (2018) Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. Renew Sustain Energy Rev 82:14–24. https://doi.org/10.1016/J.RSER.2017.09.013
152. Ruparathna R, Hewage K, Sadiq R (2017) Rethinking investment planning and optimizing net zero emission buildings. Clean Technol Environ Policy 19(6):1711–1724. https://doi.org/10.1007/s10098-017-1359-4
153. H. Amini Toosi and M. Lavagna, "Life Cycle Sustainability Assessment (LCSA) and Optimization Techniques. A conceptual framework for integrating LCSA into designing energy retrofit scenarios of existing buildings," in The 12th Italian LCA network conference. Life cycle thinking in decision making for sustainability: from public policies to private business. University of Messina, Italy 11–12 JUNE 2018, 2018, pp. 276–284, doi: ISBN: 978–88–8286–372–2.
154. H. Amini Toosi and M. Lavagna, "Optimization and LCSA-based design method for energy retrofitting of existing buildings," in Designing Sustainability for All, Proceedings of the 3rd LeNS World Distributed Conference, Milano, Mexico City, Beijing, Bangalore, Curitiba, Cape Town, 3–5 April 2019, VOL.1, 2019, pp. 1107–1111, doi: ISBN: 978–88–95651–26–2.

155. V. Machairas, A. Tsangrassoulis, and K. Axarli, "Algorithms for optimization of building design : A review," vol. 31, no. 1364, pp. 101–112, 2014, doi: https://doi.org/10.1016/j.rser.2013.11.036.
156. Chantrelle FP, Lahmidi H, Keilholz W, El Mankibi M, Michel P (2011) Development of a multicriteria tool for optimizing the renovation of buildings. Appl Energy 88(4):1386–1394. https://doi.org/10.1016/J.APENERGY.2010.10.002
157. Risholt B, Time B, Grete A (2013) Sustainability assessment of nearly zero energy renovation of dwellings based on energy, economy and home quality indicators. Energy Build. 60:217–224. https://doi.org/10.1016/j.enbuild.2012.12.017
158. Gustafsson M, Swing M, Are J, Bales C, Holmberg S (2016) Techno-economic analysis of energy renovation measures for a district heated multi-family house. Appl Energy 177:108–116. https://doi.org/10.1016/j.apenergy.2016.05.104
159. Pal SK, Takano A, Alanne K, Siren K (2017) A life cycle approach to optimizing carbon footprint and costs of a residential building. Build Environ 123:146–162. https://doi.org/10.1016/j.buildenv.2017.06.051
160. Ramin H, Hanafizadeh P, Ehterami T, AkhavanBehabadi MA (2017) Life cycle-based multi-objective optimization of wall structures in climate of Tehran. Adv. Build. Energy Res. 2549:1–14. https://doi.org/10.1080/17512549.2017.1344137
161. Moschetti R, Brattebø H (2017) Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects. Energies. https://doi.org/10.3390/en10111851
162. Ylmén P, Mjörnell K, Berlin J, Arfvidsson J (2017) The influence of secondary effects on global warming and cost optimization of insulation in the building envelope. Build Environ 118:174–183. https://doi.org/10.1016/J.BUILDENV.2017.03.019
163. Gustafsson M et al (2017) Economic and environmental analysis of energy renovation packages for European office buildings. Energy Build. 148:155–165. https://doi.org/10.1016/j.enbuild.2017.04.079
164. Mauro G et al (2017) A Multi-Step Approach to Assess the Lifecycle Economic Impact of Seismic Risk on Optimal Energy Retrofit. Sustainability 9(6):989. https://doi.org/10.3390/su9060989
165. Almeida M, Ferreira M (2017) Cost effective energy and carbon emissions optimization in building renovation (Annex 56). Energy Build. 152:718–738. https://doi.org/10.1016/j.enbuild.2017.07.050
166. M. Almeida, "Relevance of Embodied Energy and Carbon Emissions on Assessing Cost Effectiveness in Building Renovation — Contribution from the Analysis of Case Studies in Six European Countries," pp. 1–18, 2018, doi: https://doi.org/10.3390/buildings8080103.
167. J. Jokisalo, P. Sankelo, J. Vinha, K. Sirén, and R. Kosonen, "Cost optimal energy performance renovation measures in a municipal service building in a cold climate," in E3S Web of Conferences 111, CLIMA 2019, 2019, vol. 3022, no. 201 9, doi: https://doi.org/10.1051/e3sconf/201911103022.
168. S. Amirhosain and A. Hammad, "Developing surrogate ANN for selecting near-optimal building energy renovation methods considering energy consumption , LCC and LCA," J. Build. Eng., vol. 25, no. April, p. 100790, 2019, doi: https://doi.org/10.1016/j.jobe.2019.100790.
169. J. Hirvonen, J. Jokisalo, J. Heljo, and R. Kosonen, "Optimization of emission reducing energy retrofits in Finnish apartment buildings," E3S Web Conf. 111, CLIMA 2019, vol. 2, no. 2019, 2019, doi: https://doi.org/10.1051/e3sconf/2019111030.
170. Conci M, Konstantinou T, Van Den Dobbelsteen A, Schneider J (2019) Trade-off between the economic and environmental impact of different decarbonisation strategies for residential buildings. Build Environ 155(January):137–144. https://doi.org/10.1016/j.buildenv.2019.03.051
171. R. Mateus, S. M. Silva, and M. G. De Almeida, "Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings," Renew. Energy, vol. 137, pp. 82–92, 2019, doi: https://doi.org/10.1016/j.renene.2018.04.036.

172. A. Dalla Valle, A. Campioli, and M. Lavagna, "Life cycle BIM-oriented data collection: A framework for supporting practitioners," in Research for Development, Springer, 2020, pp. 49–59.
173. Lu Y, Wu Z, Chang R, Li Y (2017) Building Information Modeling (BIM) for green buildings: A critical review and future directions. Autom Constr 83:134–148. https://doi.org/10.1016/J.AUTCON.2017.08.024
174. Najjar M, Figueiredo K, Palumbo M, Haddad A (2017) Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. J. Build. Eng. 14:115–126. https://doi.org/10.1016/J.JOBE.2017.10.005
175. Shadram F, Johansson TD, Lu W, Schade J, Olofsson T (2016) An integrated BIM-based framework for minimizing embodied energy during building design. Energy Build. 128:592–604. https://doi.org/10.1016/j.enbuild.2016.07.007
176. Hollberg A, Ruth J (2016) LCA in architectural design—a parametric approach. Int J Life Cycle Assess 21(7):943–960. https://doi.org/10.1007/s11367-016-1065-1
177. Antón LÁ, Díaz J (2014) Integration of life cycle assessment in a BIM environment. Procedia Eng. 85:26–32. https://doi.org/10.1016/j.proeng.2014.10.525
178. Eleftheriadis S, Mumovic D, Greening P (2017) Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. Renew Sustain Energy Rev 67:811–825. https://doi.org/10.1016/J.RSER.2016.09.028
179. Barlish K, Sullivan K (2012) How to measure the benefits of BIM — A case study approach. Autom Constr 24:149–159. https://doi.org/10.1016/J.AUTCON.2012.02.008
180. Bryde D, Broquetas M, Volm JM (2013) The project benefits of Building Information Modelling (BIM). Int J Proj Manag 31(7):971–980. https://doi.org/10.1016/J.IJPROMAN.2012.12.001
181. Kota S, Haberl JS, Clayton MJ, Yan W (2014) Building Information Modeling (BIM)-based daylighting simulation and analysis. Energy Build. 81:391–403. https://doi.org/10.1016/J.ENBUILD.2014.06.043
182. Soust-Verdaguer B, Llatas C, García-Martínez A (2017) Critical review of bim-based LCA method to buildings. Energy Build. 136:110–120. https://doi.org/10.1016/J.ENBUILD.2016.12.009
183. Malmqvist T et al (2011) Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. Energy 36(4):1900–1907. https://doi.org/10.1016/J.ENERGY.2010.03.026
184. Peng C (2016) Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. J Clean Prod 112:453–465. https://doi.org/10.1016/J.JCLEPRO.2015.08.078
185. N. Shafiq, M. F. Nurrudin, S. S. S. Gardezi, and A. Bin Kamaruzzaman, "Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM)," Int. J. Sustain. Build. Technol. Urban Dev., vol. 6, no. 3, pp. 157–172, Jul. 2015, doi: https://doi.org/10.1080/2093761X.2015.1057876.
186. Basbagill J, Flager F, Lepech M, Fischer M (2013) Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build Environ 60:81–92. https://doi.org/10.1016/J.BUILDENV.2012.11.009
187. Ajayi SO, Oyedele LO, Ceranic B, Gallanagh M, Kadiri KO (2015) Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment. Int J Sustain Build Technol Urban Dev 6(1):14–24. https://doi.org/10.1080/2093761X.2015.1006708
188. Jalaei F, Jrade A (2014) An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects. J Constr Eng 2014:1–21. https://doi.org/10.1155/2014/672896
189. Lee S, Tae S, Roh S, Kim T (2015) Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. Sustainability 7(12):16498–16512. https://doi.org/10.3390/su71215830
190. J. Basbagill, F. Flager, M. Lepech, and M. Fischer, "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts," Build. Environ., vol. 60, pp. 81–92, Feb. 2013, doi: https://doi.org/10.1016/J.BUILDENV.2012.11.009.

191. A. Houlihan Wiberg et al., “A net zero emission concept analysis of a single-family house,” Energy Build., vol. 74, pp. 101–110, May 2014, doi: https://doi.org/10.1016/J.ENBUILD.2014.01.037.
192. B. Berg, “Using Bim To Calculate Accurate Building Material Quantities for Early Design Phase Life Cycle Assessment,” 2014.
193. Dupuis M, April A, Lesage P, Forgues D (2017) Method to enable LCA analysis through each level of development of a BIM model. Procedia Eng. 196:857–863. https://doi.org/10.1016/J.PROENG.2017.08.017