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BUILDING COMPONENTS AND BUILDINGS

The application of life cycle assessment in buildings: challenges, and directions for future research

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Abstract

Purpose This paper reviews the state-of-the art research in life cycle assessment (LCA) applied to buildings. It focuses on current research trends, and elaborates on gaps and directions for future research.

Methods A systematic literature review was conducted to identify current research and applications of LCA in buildings. The proposed review methodology includes (i) identifying recent authoritative research publications using established search engines, (ii) screening and retaining relevant publications, and (iii) extracting relevant LCA applications for buildings and analyzing their underpinning research. Subsequently, several research gaps and limitations were identified, which have informed our proposed future research directions.

Results and discussions This paper argues that humans can attenuate and positively control the impact of their buildings on the environment, and as such mitigate the effects of climate change. This can be achieved by a new generation of LCA methods and tools that are model based and continuously learn from real-time data, while informing effective operation and management strategies of buildings and districts. Therefore, the consideration of the time dimension in product system modeling is becoming essential to understand the resulting pollutant emissions and resource consumption. This time dimension is currently missing in life cycle inventory databases. A further combination of life cycle impact assessment (LCIA) models using time-dependent characterization factors can lead to more comprehensive and reliable LCA results.

Conclusions and recommendations This paper promotes the concept of semantic-based dynamic (real-time) LCA, which addresses temporal and spatial variations in the local built and environmental ecosystem, and thus more effectively promotes a "cradle-to-grave-to-reincarnation" environmental sustainability capability. Furthermore, it is critical to leverage digital building resources (e.g., connected objects, semantic models, and artificial intelligence) to deliver accurate and reliable environmental assessments.

Keywords Life cycle assessment (LCA) · Building information modeling (BIM) · Dynamic data · Semantic models · Machine learning (ML)

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1 Introduction

Globally, the population of cities is predicted to grow to 68% by 2050 (UN 2019). However, cities are currently responsible for 75% of global energy consumption and greenhouse gas (GHG) emissions, with over 40% of total energy consumption attributed to buildings (IEA 2018). Moreover, the building sector is recognized as a key consumer of natural resources. It is also responsible for one-third of European waste and 22% of European hazardous waste production (EC 2011). The special report on the impact of global warming of 1.5 °C (Stocker et al. 2013) was yet another call to implement measures to mitigate GHG emissions and to devise new adaptation scenarios. In this context, life cycle assessment (LCA) can help to quantify the environmental pressures, the trade-offs, and the areas to achieve improvements considering the full life cycle of buildings, from design to recycling. However, current approaches to LCA do not consistently factor in (both in the foreground and background inventory systems) life cycle variations in (a) building usage, (b) energy supply (including from renewable sources), and (c) building and environmental regulations; as well as other changes over the building/district lifetime (Anand and Amor 2017; Bueno et al. 2016; Skaar and Jørgensen 2013). These include (a) change in the energy mix of a building/district or upgrading/retrofitting the energy system(s) in place and (b) time increase of energy demand during the lifetime of a building due to a wide range of reasons, including changes in occupancy patterns.

LCA is an important instrument to help reduce the overall environmental burden of buildings and provide insights into the upstream and downstream trade-offs that are associated with environmental pressures, health and wellbeing, and the consumption of natural resources. As such, LCA can inform policymaking by providing valuable information on the environmental performance of buildings. However, the current LCA methods and tools face several limitations and challenges, including: (a) site-specific considerations (Bueno et al. 2016), several local impacts need to be considered in building assessments, such as the microclimate; (b) model complexity (Anand and Amor 2017), buildings involve a wide range of material/products, interacting as part of a complex assembly or system; (c) scenario uncertainty (Anand and Amor 2017; Bueno et al. 2016), the long use phase of buildings, including the potential for future renovation, poses uncertainty problems in LCA that are not currently addressed; (d) health and well-being (Bueno et al. 2016; Skaar and Jørgensen 2013), traditional LCA methodologies do not address indoor and outdoor environmental impacts on health and well-being; (e) recycled material data (Anand and Amor 2017; Negishi et al. 2018), lack of data on using waste and recycled materials as new building materials; and (f) lack of consideration for social and economic aspects (Anand and Amor 2017; Negishi et al. 2018).

Current LCA methods present some further important limitations and gaps, including:

- Lack of reasoning and decision support capabilities, such as exploring "what if" scenarios for the evaluation of alternative design options and devising adapted strategies, thus promoting active control of buildings and districts (Skaar and Jørgensen 2013).
- Lack of alignment with domain models, such as building information modelling (BIM), geographical information systems (GIS), and LCA data structures (García-Pérez et al. 2018; Soust-Verdaguer et al. 2017).
- Lack of full support of temporal information (Anand and Amor 2017; Bueno et al. 2016; Cardellini et al. 2018; Tiruta-Barna et al. 2016). There is a need to factor in temporal information in the background and foreground life cycle inventory (LCI), and life cycle impact assessment (LCIA) phases to address maintenance, operation, deconstruction, disposal, and recycling stages.

Recent research has used more advanced approaches to LCA (Negishi et al. 2018; Skaar and Jørgensen 2013), such as incorporating economic considerations by including life cycle cost analysis. There is also a growing interest in the integration of BIM with environmental impact calculation methods (Soust-Verdaguer et al. 2017). However, this work is currently limited by semantic incompleteness and interoperability issues between current software solutions. In addition, efforts to scale up LCA from building to district levels are limited (Anand and Amor 2017; Soust-Verdaguer et al. 2017).

The application of LCA for buildings requires informed interventions to achieve carbon neutrality, including the elaboration of carbon-intensive activities. These decarbonization strategies use optimization approaches to reduce material and energy demand, while integrating renewables and achieving a higher order of efficiency of resources. Carbon neutrality assessment can be also applied and scaled to a district level by adopting reduction and avoidance strategies, and adapted analysis of the value chain (Andrews 2014).

This paper aims to identify evidence and best practices for the implementation of LCA in buildings, focusing on the gaps and limitations in current applications. This aim translates into the following research questions:

(a) What is the state-of-the-art research landscape in LCA applied to buildings?
(b) What are the gaps and limitations of current applications of LCA in buildings?
(c) What are the directions for future LCA research?

To answer these research questions, a set of relevant LCA concepts are explored alongside their relationship with existing practices, ranging from responsible design and modeling techniques to embodied impacts and renovation strategies. The integration of LCA with BIM is also examined, with insights for the development of interoperable strategies.

The structure of this paper mirrors the research questions. Following this introduction, an overview of the methodology that underpins this review is given. "Sect. 3" explores some of the current trends in LCA applied to buildings. "Sect. 4" will then elaborate on the existing gaps and limitations in LCA research, which is followed by a proposal for directions for future research. Finally, "Sect. 6" draws a conclusion.

2 Methodology

A systematic review has been conducted to identify the current research topics and applications of LCA for buildings (Fig. 1). The methodology used to conduct the review involved three main stages:

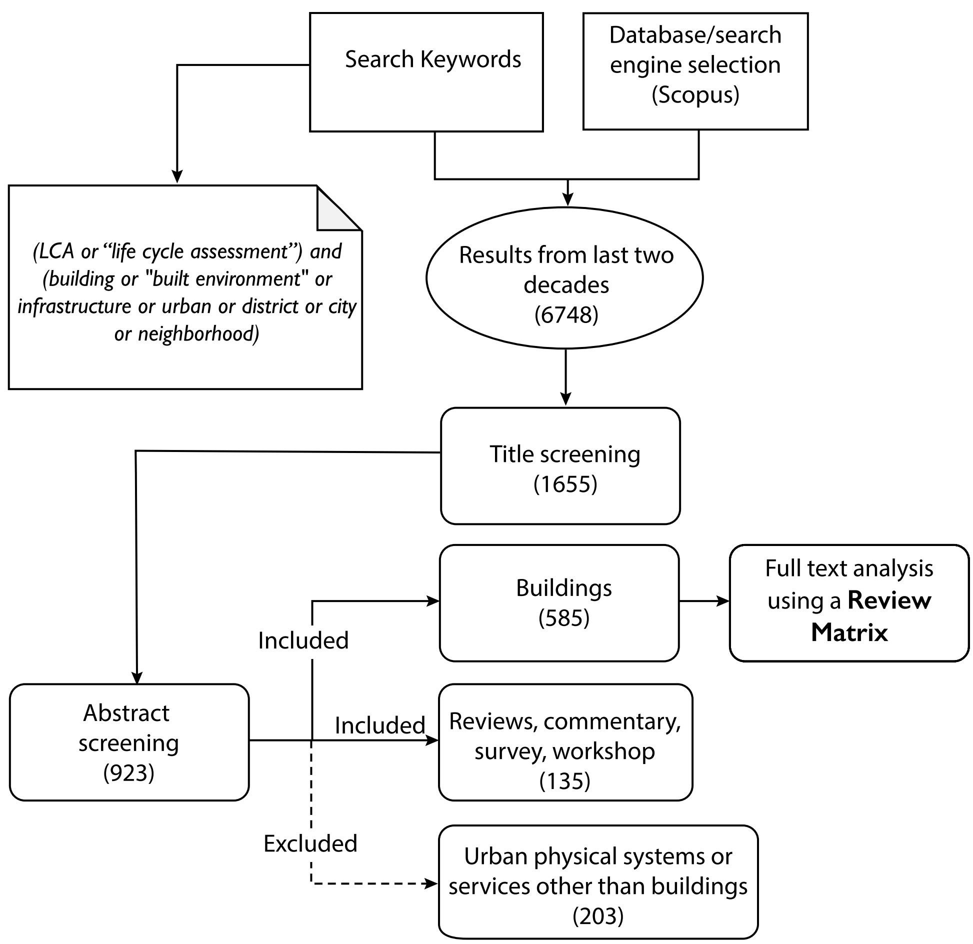
Stage 1: Identifying recent authoritative research publications using established search engines

Relevant documents were retrieved from SCOPUS using a set of keywords. The following keywords were selected to provide a broad and comprehensive perspective to address the posited research questions: (LCA OR "Life Cycle Assessment") AND ("Building" OR "Built Environment" OR "Infrastructure" OR "Urban" OR "District" OR "City" OR "Neighborhood"). Initially, this combination of keywords returned 6748 documents, including journal articles, conference paper, book chapters, and reports.

Stage 2: Screening and retaining relevant publications

As shown in Fig. 2, research in LCA of the built environment is rapidly growing, especially in the past 10 years. Due to the sheer number of documents published per year, and the incremental nature of the published research, this review will focus on LCA research applied to buildings only from relevant recent publications that were published in the last 5 years, while acknowledging seminal work in the past 10 years. Initial screening of the retrieved documents was carried out to identify relevant studies. In this step, the titles and abstracts of 1655 documents were examined to determine whether the study meets the objectives of this review. As a results, a list of 923 documents was created. This list

Fig. 1 Flow chart of the literature review methodology



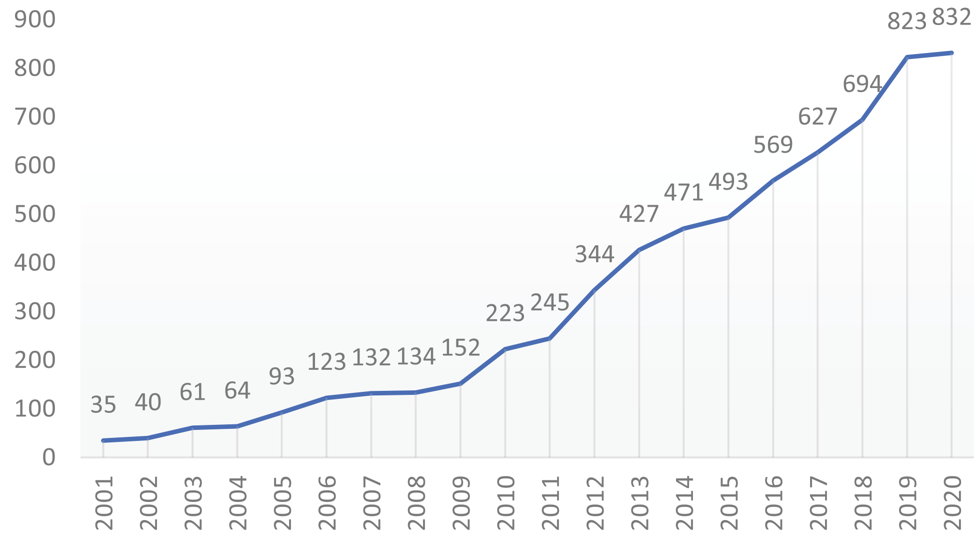


Fig. 2 Number of built environment LCA publications over the past 20 years

is then divided into three categories: buildings, other urban physical systems (e.g., utilities, transportation system, open spaces, and waste treatment facilities), and existing reviews, commentaries, and surveys (Fig. 3). Since this paper focuses on buildings, studies related to infrastructure and physical assets other than buildings are excluded from further in-depth analysis. Studies were included if LCA is directly applied to buildings, or to building materials and products.

Stage 3: Extracting relevant LCA use cases applied to buildings and analyzing their underpinning research

A framework has been developed to systematically explore each study to its full extent. The proposed framework aims to identify the different use cases and highlight the current research trends of LCA for buildings. The following information was collected for each study: (1) scale: this reveals information about building typology and the number of buildings involved in the study; (2) area of application: studies were categorized based on the main objective of conducting LCA, for example, if a study developed scenarios to enhance the energy performance of existing buildings, then the study is labeled as "energy retrofit"; (3) scope: this gives a brief description of the overall goal of the study; (4) use of BIM and domain models: to identify studies that utilized BIM, or other domain models as part of the framework; (5) utilization of dynamic data: to capture the use of real-time data in LCA using sensors, smart meters, and IoT devices; (6) consideration of end users or occupants: identifies the role of human behaviors and feedback on LCA results; (7) impact on human health and well-being: the aim is to identify studies that have considered the impact of the indoor environment on the occupant's health and well-being; (8) sustainability dimensions: the integration of different sustainability aspects, namely environmental, economic, and social. The outcomes of the proposed framework are presented in the following section.

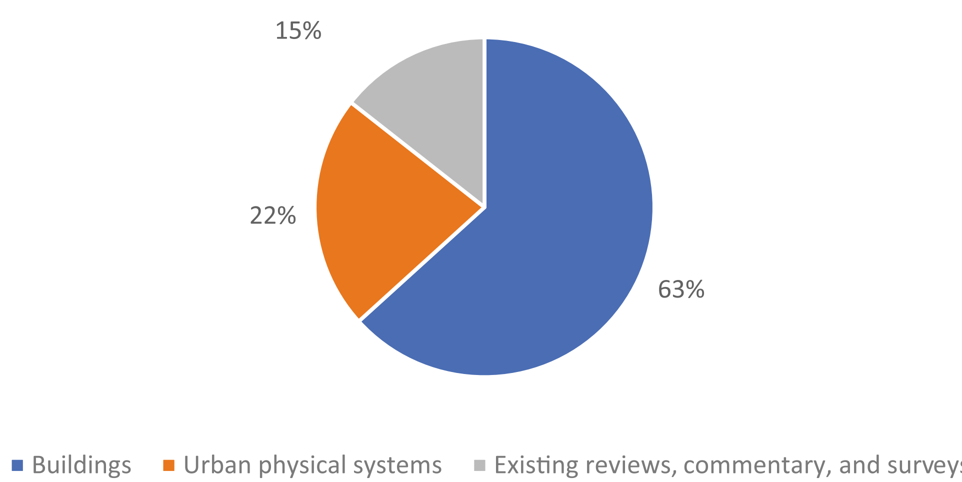


Fig. 3 Distribution of scientific publications according to scale of application (asset level to urban level) and type of research

3 State-of-the-art research landscape in LCA

A thorough review was conducted to elicit the information required by the proposed framework (see "Sect. 2"). Previous reviews on the application of LCA in buildings over the past two decades have identified that most studies focus on energy use and GHG emissions (Asif 2019; Elkhayat et al. 2020; Lyu and Chow 2020). Furthermore, researchers have applied LCA methodology on key areas related to the decarbonization of buildings. One of the main objectives of the study is to identify the different use cases of LCA applications in buildings. The use cases were identified through an iterative process that involved extracting from each identified paper: (a) area of application and (b) scope. The second stage involved factoring these findings into a set of generic use cases. As such, the structure of this section followed a use case-based approach. This approach helps to provide an overview of each particular application of LCA, evaluate the current progress, and identify key challenges and limitations of each area. Figure 4 reveals the most common use cases of building LCA. This figure also shows the number of LCA studies per use case. The following subsections will elaborate on each identified use case, starting from the most highly researched.

3.1 Environmentally responsible design

LCA is increasingly being applied to evaluate the environmental impacts of buildings during the design phase. Various aspects must be considered when performing LCA at the design stages, such as the need for rapid assessment of design variants (Budig et al. 2020); the lack of available information, especially in the early-design phase; and the other aspects of sustainability, such economic and social dimensions. This review has identified three categories of LCA application during the design stage, namely frameworks, comparative LCA studies, and integrating LCA with other modeling techniques.

The first category includes studies that have developed frameworks to facilitate the workflow of conducting LCA during the design stage, and have proposed a simplified screening approach to select material and structural systems during the early-design stages (Budig et al. 2020). The computational workflow assesses the environmental impacts of various configurations of building design and it assists designers in making environmentally informed decisions, especially when design requirements and material information are vaguely specified. Zeng et al. (2020) integrated design, cost effectiveness, and embodied impacts to facilitate the selection of structural and envelope systems during the early-design stages. Asadi et al.'s (2019) study introduced a multi-criteria decision-making model that combines structural resilience with environmental and economic assessment. Hasik et al. (2019) developed a framework to estimate the impacts of material use and energy and water consumption by integrating concepts such as LCA, LCC, energy modeling, and seismic loss analysis.

The second category includes comparative LCA studies that consider multiple environmental, economic, and social indicators to identify the design alternative with the lowest environmental impacts, for example: environmental performance of various slab systems (Paik and Na 2020); assessment of GHG emissions and energy demand

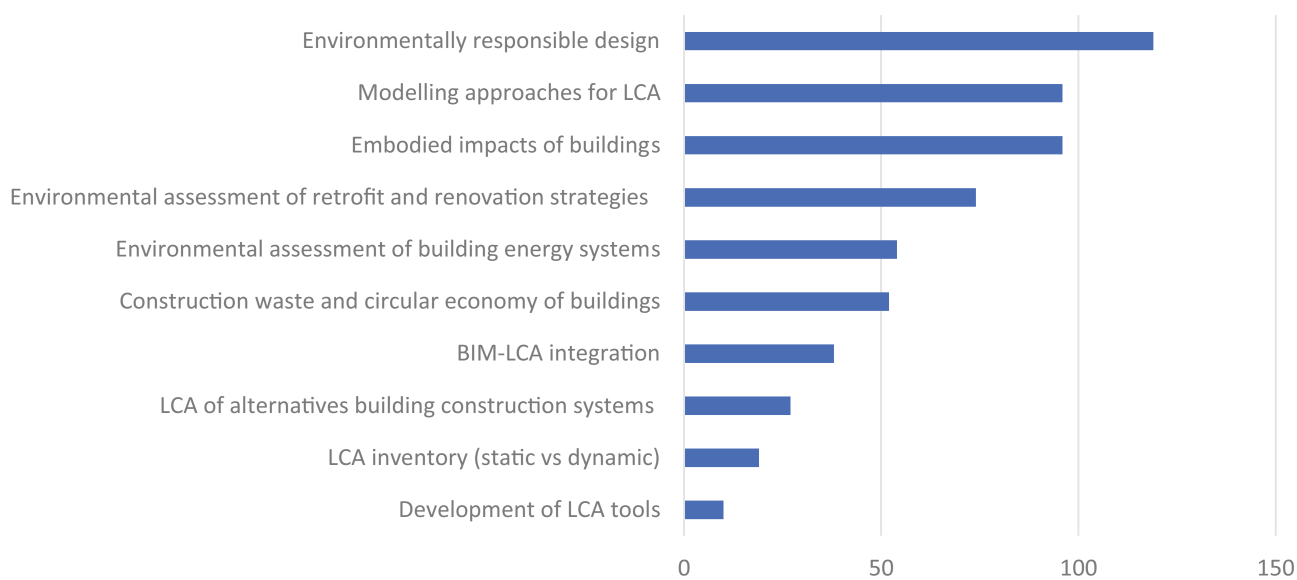


Fig. 4 The number of recent LCA studies conducted on use cases issues related to buildings

of five structural systems (Shrestha 2021); assessment of window-to-wall ratio (WWR) showed that higher WWR results in higher environmental impacts and economic costs and dissatisfied occupants (Phillips et al. 2020); the impact of structural design methods on GHG emission (Helal et al. 2020); the impact of material selection on carbon emissions during design (Luo and Lu 2020).

The third category includes studies that integrate LCA methodology with computational and analytical techniques, such as machine learning, optimization, and DEA. For example, Kiss and Szalay (2020) developed a parametric multi-objective optimization approach to minimize the environmental impacts of different building systems, including envelope, heating, and energy systems. In Manni et al. (2020), a parametric multi-objective optimization model was developed to minimize the embodied carbon and maximize solar irradiation by varying building geometry and orientation. Wang et al. (2020) developed a trade-off optimization-based framework for thermal comfort, life cycle cost, and environmental impacts of building envelope. Płoszaj-Mazurek et al. (2020) built a parametric machine-learning model to predict carbon footprint using basic design parameters such as wall area, roof area, and height. Finally, Tavana et al. (2021) used DEA-based LCA to compare the environmental performance of flooring covering systems.

As noted earlier in this section, conducting a thorough assessment of a given building design is challenging during early design stages due to the lack of detailed information and the sheer number of input parameters, which make it difficult to explore trade-off solutions (Budig et al. 2020; Liu and Bakshi 2018). Nevertheless, the reviewed studies show that developing decision support systems using machine learning and optimization methods can be useful in certain aspects of the LCA. Machine learning thrives in data intensive applications (e.g., LCA) as it can be used in optioneering and the decision-making processes for identifying the most informative parameters (Sharif and Hammad 2019), therefore reducing the cost and time needed to gather the required data. Furthermore, optimization methods are particularly useful in the design process due to their capability of exploring potential improvement options.

3.2 Modeling approaches for LCA

This section discusses some of the methodological approaches that have aimed to solve issues related to the generic LCA framework, such as treatment of uncertainty, interpretation of LCA results, and the inclusion of other sustainability dimensions.

3.2.1 Interpretation of LCA results

Reporting and drawing conclusions based on quantified environmental metrics that do not always correspond to absolute target values, such as planetary boundaries, is a standard practice in LCA studies. To address this issue, Andersen et al. (2020) developed a top-down approach to determine whether or not an environmentally optimized building design falls within some absolute values, such as the earth's carrying capacity and the planetary boundaries. The findings indicate that resource reuse and recycling, as well as reducing operational energy use, are the most effective strategies for meeting sustainability goals. Another top-down approach was proposed, whereby the building industry is assigned a share of a country's overall carbon budget (Chandrakumar et al. 2020). Meanwhile, Rucinska et al. (2020) used a different approach to set the target values for the building sector by focusing on local regulatory requirements and the environmental performance of existing buildings to statistically determine the benchmark values. Similarly, Rasmussen et al. (2019) calculated reference benchmarks for residential buildings using national samples. They emphasized the importance of having consistent calculation rules and transparent benchmark framework. Another challenge of interpreting LCA results is that environmental indicators are difficult for stakeholders to understand, especially non-LCA experts; hence, the concept of monetary valuation of environmental impacts was introduced. Schneider-Marin and Lang (2020) investigated several monetary valuation models and applied them to the embodied impacts of six German office buildings. According to this study, the most important environmental indicators recognized by the construction industry are global warming potential (GWP), resource depletion, and acidification potential.

3.2.2 End-of-life treatment

Enabling circular economy in the building sector presents the LCA community with methodological challenges regarding end-of-life treatment and the allocation of benefits and burdens across multiple life cycles of products and materials. Eberhardt et al. (2020) noted that the existing allocation approaches significantly differ in the distribution of impacts between cycles and their allocation of incentives is questionable. As a result, they proposed a theoretical model that is based on an existing approach (i.e., linear regressive) to support the transition towards a circular practice. Following a review of two widely used LCA methods, namely product environmental footprint (PEF) and CEN EN 15804/15978, it was found that existing databases (e.g., Ecoinvent) are incompatible with the end-of-life treatment of both methods

(Mirzaie et al. 2020). The authors also argued that harmonizing the two methods is important to obtain more comparative and reliable LCA results.

3.2.3 Uncertainty

The difficulty in conducting an environmental assessment of a product is that practitioners often work with incomplete and unreliable information, and in some cases they have to work with unascertained information (He et al. 2018). This leads to various levels of uncertainty in LCA results. Several studies have attempted to categorize and describe uncertainty sources in LCA studies. The ILCD handbook (EC-JRC 2010) identified three sources of uncertainty: stochastic uncertainty, choice uncertainty, and lack of knowledge of the studied system. Meanwhile, X. Zhang et al. (2020a) identified three types of uncertainty in the literature: model uncertainty, scenario uncertainty, and parameter uncertainty.

In addition, researchers have addressed the issue of uncertainty using a range of approaches. Table 1 describes the numerous uncertainty sources in LCA for buildings, the calculation methods applied to quantify uncertainty, the input parameters used in the calculation models, and the extent to which each source of uncertainty contributes to the building's overall impact. For example, Goulouti et al. (2020) applied a probabilistic approach to determine the replacement rate of building elements considering their service life, while Ianchenko et al. (2020) used a probabilistic survival model to address the uncertainty of building service life. Morales et al. (2020) assessed the uncertainties associated with the replacement stage considering service life of building elements and LCI data quality. Harter et al. (2020) studied the impact of building development level and shape on the level of uncertainty in LCEA during the early-design stage using a variance-based approach. Resalati et al. (2020) examined the effect of embodied energy data uncertainty on the total carbon emissions for the design of a building envelope. Other researchers have modeled the uncertainty of embodied CO_2 emissions of different building materials considering a building's lifetime and transport distance (Robati et al. 2019). In Ylmén et al. (2020), a framework was developed to manage choice uncertainty (e.g., design options) in the early-design stages.

3.2.4 Dynamic LCA

A dynamic LCA framework (DLCA) has four elemental dynamic components, namely consumption data, basic inventory datasets, characterization factors, and weighting factors (Su et al. 2019a). Using DLCA, Rosse Caldas et al. (2020) evaluated the impact of climate change on the environmental performance of a bamboo bio-concrete building considering several factors, including the anticipated increase in temperature, changes in grid mix, and dynamic characterization factors. A dynamic weighting system was developed to support time-dependent environmental and planning policies (Su et al. 2019b). Zieger et al. (2020) conducted a comparative study between static LCA and dynamic LCA by considering the temporal dynamics of GHGs. It was found that static LCA, combined with other factors, leads to misleading conclusions regarding bio-based materials, while the dynamic LCA (DLCA) model is more realistic because it considers the

Table 1 Reviewed uncertainty studies related to building LCA

References	Uncertainty sources	Calculation method	Main input parameters	Life cycle stage contribution
(Goulouti et al. 2020)	Replacement rate, reference service life of the building	Probabilistic	Service life of building elements	36% of GHG emissions is attributed to the replacement stage
(Harter et al. 2020)	Building development level, building shape	Variance-based method	Geometrical, technical, window, building operation, system efficiency	-
(Morales et al. 2020)	LCI data, service life of building elements	Monte Carlo simulation and scenario-based approach	Replacement scenarios	The developed scenarios, life cycle data, and impact categories influence the results of the use stage contribution to the overall impact
(Ylmén et al. 2020)	Choice uncertainty	Structured approach and Monte Carlo simulation	Design options	-
(Robati et al. 2019)	Lifespan, transport distance, embodied CO_2-e emissions	Monte Carlo simulation	Building materials	-
(Ianchenko et al. 2020)	Service life	Probabilistic approach and Bayesian information criteria	Building lifespan	-

timing of GHG releases and uptakes. Similarly, Negishi et al. (2019) noticed significant differences in the results when both static and dynamic models were used, particularly for bio-based materials. Collinge et al. (2018) evaluated the "importance of using temporally resolved building-level data while capturing the effects that a changing electrical grid has on the life cycle impacts of buildings" and "concluded that a "standard" LCA underestimates the use phase impacts."

3.3 The embodied impact of buildings

Concerns related to the environmental impacts of operational energy use in new buildings are diminishing as a result of effective energy retrofit strategies (Sicignano et al. 2019). A major consequence of enhancing energy efficiency of buildings is the increase in embodied impacts because of the required additional materials, which involve transferring the environmental burden from the use phase to other phases (Asdrubali et al. 2019). Therefore, focusing on material efficiency is critical to mitigate the environmental impacts of buildings (Lausselet et al. 2020). Several material efficiency strategies have been identified, including intense use and lifetime extension of buildings, the use of lighter and low carbon construction materials, minimizing construction waste, and the reuse and recycling of building components (Hertwich et al. 2019). As previously mentioned, one of the key areas of current research is the reduction of the embodied emissions of construction materials. Table 2 identifies the most common buildings materials and summarizes the main objectives of the reviewed studies. For instance, Kylili and Fokaides (2019) investigated the environmental benefits of alternative construction products that incorporate recycled or natural materials. When compared to other building materials, timber has a lower environmental impact with the added benefit of carbon sequestration (Hill 2019). Moreover, there is growing interest in alternative bricks produced with organic and inorganic wastes, which originate in other industries, while research on traditional bricks is decreasing (Ramos Huarachi et al. 2020). However, while alternative building materials have many environmental benefits, understanding the extent of their impact is a key barrier to their adoption, along with other important considerations, such as reducing costs and eliminating regulatory barriers (Krueger et al. 2019). Although substantial reduction in GHG emissions can be accomplished from a technological perspective, other aspects of material efficiency strategies must be considered, namely economic, social, and environmental (Hertwich et al. 2019). Intensive use of building materials and the lifetime extension of products are the most effective material efficiency strategies identified by this study.

Table 2 Studies on LCA of common construction materials

References	Material	Objectives
(Dandautiya and Singh 2019; Ellingboe et al. 2019; Horn et al. 2019; Kurda et al. 2019; Oladazimi et al. 2020; Shi et al. 2019; Václavík et al. 2020; Wei et al. 2020; Welsh-Huggins et al. 2020)	Concrete	-Evaluating the environmental impacts of concrete using recycled aggregate and other waste materials, fly ash, steel slag, kaolin clay, and bio-based materials -Comparative LCA of concrete with other materials, such as steel
(Chen et al. 2019; Nakano, Karube et al. 2020; Nakano, Koike et al. 2020; Pierobon et al. 2019; Puettmann et al. 2019)	Wood	-Focusing on production of wood-based products (e.g., CLT), logistical challenges and the environmental assessment of timber construction
(Akyüz 2020; Amani and Kiaee 2020; Bottino-Leone et al. 2019; Casas-Ledón et al. 2020; Silvestre et al. 2019; Sun et al. 2020; Torres-Rivas et al. 2021; Wiprächtiger et al. 2020)	Insulation materials	-Economic and environmental assessment of insulation materials -Selection of thermal insulation using optimization approaches -Evaluation of bio-based insulation materials
(Di Bari et al. 2020; Fabiani et al. 2020; Konstantinidou et al. 2019; Motte et al. 2019; Papadaki et al. 2019)	Phase change materials	-Environmental assessment of using PCM for thermal application and energy savings
(AzariJafari et al. 2019; Çankaya and Pekey 2019; Gettu et al. 2019; Long et al. 2019; Vázquez-Rowe et al. 2019; Zulcão et al. 2020)	Cement	-Mostly related to cement production and cement replacement materials
(Fernandes et al. 2019; Meek et al. 2021; Narayanaswamy et al. 2020)	Earthen materials	-Environmental and thermal assessment of alternative building products such as rammed earth and compressed earth blocks

3.4 Environmental assessment of retrofit and renovation strategies

Existing building stock rehabilitation measures are generally applied to enhance thermal performance and reduce operational energy use. Improvement to the building's envelope, energy system, and energy end-use are the main focus of building rehabilitation studies, while non-energy-related rehabilitation measures are usually ignored (Thibodeau et al. 2019). Similarly, Vilches et al. (2017) found that energy retrofit, primarily through increased insulation, is the most commonly applied measure, while structural repairs are mostly overlooked. Although the aim of energy retrofitting is to reduce energy consumption during the use phase, the environmental impacts of the applied retrofit measures differ significantly across different life cycle stages (Oregi et al. 2017). Galimshina et al. (2020) applied statistical methods to select the most efficient renovation measure under environmental and economic considerations. Another study considered similar retrofit scenarios and used data envelopment analysis in combination with linear regression to select the most efficient retrofit scenario (Belucio et al. 2021). Other researchers have utilized artificial neural networks (ANNs) to determine the near-optimal energy retrofit scenario taking into account environmental impacts, costs, and energy consumption (Sharif and Hammad 2019). Rather than considering different retrofit measures, Pittau et al. (2019) carried out a comparative LCA of several bio-based insulation materials of the exterior walls of European housing stock.

Table 3 provides more details for studies on LCA—guided building retrofit solutions. Details are provided for each study regarding the retrofit proposals, scale of application (e.g. individual buildings vs district/urban level), models and analytical methods employed to evaluate the proposed solutions, as well as the set of parameters used to estimate and optimize the environmental performance of each retrofit measure. One of the most noticeable differences between small scale application (i.e., building level) and large-scale application (i.e., district level) is the level of data granularity. While studies concerned with individual buildings were able to utilize more detailed parameters, such as heating set point, wall thickness/ characteristics, and operational schedules, studies at district level resorted to more generic attributes, such as floor area and the number of stories. Consequently, the accuracy and reliability of LCA outcomes significantly differ. Therefore, methods are needed to provide accurate accounts of building environmental impacts when considering LCA at district and wider levels. This may involve the reliance on simulation models that can be developed based on a typology of buildings within a district. This can be facilitated by the use of Building Information Models as well as having access to historical data.

3.5 Construction waste and circular economy in the building sector

The circular economy is a system that seeks to maintain materials and products in use for as long as possible, while minimizing waste generation (EC 2018). However, closing the energy and material loops through a circular model (i.e., design, use, reuse, and recycle) contrasts with the linear value chain model that is used in the building construction industry (de Wolf et al. 2020). In addition, implementing a circular economy in the building sector is hindered by several barriers, including the fact that building industry is conservative and fragmented, the lack of a unified and comprehensive framework, and because buildings are usually developed under time and cost constraints (Futas et al. 2019). Hence, realizing the benefits of a circular economy in buildings requires changes to the industry practice (Giorgi et al. 2020).

Several studies have been conducted on construction waste recycling and components reuse. Ajayebi et al. (2020) developed a spatiotemporal mapping model to analyze building structural products for reuse potential in three urban areas. Their model provides critical information, such as product geometries, age, carbon emissions, and weight, which are all necessary for the assessment of future reuse scenarios. Meanwhile, Bertin et al. (2020) developed a framework to facilitate future reuse and established a material bank for structural building elements. Their methodology supports the design for reuse concept and uses the BIM framework to increase the level of details and traceability of the load-bearing elements. Other researchers developed an optimization method for designing structures from a reclaimed elements stock (Brütting et al. 2020). In a comparative LCA study, Minunno et al. (2020) concluded that the reuse of building components reduces greenhouse gas emissions by 88% when compared to recycling. However, the viability of recycling and reuse of construction material (e.g., waste bricks as a replacement to natural aggregates, cement binder, or alkaline activation) is contingent on using advanced technology and rigorous environmental characterization (Fořt and Černý 2020).

In addition to the environmental benefits of implementing circular economy strategies, the economic costs must be considered. Üçer Erduran et al. (2020) found that the environmental impacts of a new construction using reclaimed wall pieces are lower when compared to the case of using new bricks. Meanwhile, the construction costs of using reclaimed bricks are roughly twice the costs of new bricks because the reclaimed wall pieces require the use of expensive equipment. Moreover, the higher cost associated with reused elements is attributed to the additional requirements of sampling, testing, design modifications, and the limited supply of second-hand building products (Vares et al. 2020).

Table 3 LCA use cases of building retrofit measures

Reference	Intervention scenarios	Scale	Decision criteria and method	Parameters
(Galimshina et al. 2020)	Heating system, insulation of (exterior wall, slab, and roof), windows	Three residential buildings	Statistical analysis of environmental and economic costs	Component types and service life, investment costs, operation costs, user-related parameters
(Belucio et al. 2021)	Heating system, roof insulation, exterior wall insulation	Residential building	Data envelopment analysis and linear regression taking into consideration the economic costs and environmental impact	Heating and cooling system set points and efficiency, insulation material conductivity and thickness, exterior wall thickness and conductivity, windows system configuration, etc
(Pittau et al. 2019)	Exterior wall insulation	Building stock	Comparative LCA focusing on climate change impacts	Speed of renovation, service life, wall area, thermal performance, type of insulation material, thickness, and so on
(Sharif and Hammad 2019)	HVAC system, external wall, roof, façade type, window frame type	University building	ANN taking into account energy consumption, LCC and LCA	Roof surface, exterior wall characteristics, airtightness, operation schedule, temperature setting, space allocation, window design, etc
(Ghose et al. 2019)	Installation of PV panels, use of renewable energy, minimizing embodied impacts of materials	17 office buildings	Statistical approach, selection is based on environmental impacts only	Gross floor area, location, roof area, stories, façade materials, window-to-wall ratio, window type, etc
(Gulotta et al. 2021)	Thermal insulation using different materials	672 archetypes of the EU residential building stock	Selection is based on the energy and environmental performance of the studied materials	Several parameters related to general building information, and characteristics, such as location, floor area, number of stories, story height, window-to-wall ratio, U-value, and other operational data
(Oregi et al. 2020)	Several strategies applied to building envelope, heating system, thermal improvement, and the use of solar panels	Residential building	The assessment is based on four environmental and economic indicators	Generic building data, geometric and operational parameters, and economic parameters

3.6 Environmental assessment of building energy systems

Apart from their energy efficiency, sustainable buildings must produce energy on-site from renewable sources (Gouveia et al. 2020). Previous studies of on-site energy production technologies have provided insights into the costs and benefits of increasing energy self-sufficiency. Table 4 provides a summary of recent studies that have considered the use of renewable energy sources, such as PV systems, energy storage systems, ground source heat pumps, and fuel cells. Table 4 also provides information about the use of energy storage technologies, the location of the installed system relative to the building, and the main findings of the study.

In contrast, very few studies have considered the impact of operational energy use. González-Prieto et al. (2020) found that the operational energy to total impact ratio varies considerably depending on three factors: thermal energy source, local climate, and the building's shape. Gardezi and Shafiq (2019) developed a linear regression model to predict carbon emissions from operational energy using four variables, namely construction area, building volume, building lifespan, and weight. Although this study did not comment on the significance of each variable, it does provide an approach for predicting operational carbon emissions during early-design stages. Meanwhile, other factors affecting the environmental and economic impacts of energy consumption have been studied. For example, Walzberg et al. (2020) considered the possibility of a rebound effect in smart homes because the occupants' energy consumption behavior is primarily influenced by economic rather than environmental signals. The authors recommended the inclusion of environmental signal in the smart management system because the agent-based simulation model shows a five-fold increase in the rebound effect when load-shifting is driven solely by an economic signal. In addition, O'Rear et al. (2019) compared the effect of heating fuel type, specifically natural gas and electricity, on the sustainability performance of buildings. This study found that electric equipment is more likely to achieve net-zero energy performance, while having higher environmental impacts.

3.7 BIM-LCA integration

BIM is seen as a tool that simplifies the use of LCA in the building sector and provides integrated solutions to a complex and laborious framework, such as the LCA (Mora et al. 2020). The BIM-LCA integrated approach is typically used during the design stage as a decision support tool because it allows design alternatives to be explored and LCA calculations to be simultaneously conducted (Panteli et al. 2020). Furthermore, Llatas et al. (2020) found that material information and quantities are one of the main uses of coupling BIM and LCA, and that data interoperability remains a challenging issue. The integration of BIM and LCA for data exchange and feedback occurs on three levels, namely using BIM as a source of data during LCI development (e.g., bill of quantities and material information), incorporating environmental information into BIM tools, and automating the entire workflow between different software environment (Soust-Verdaguer et al. 2017). Safari and AzariJafari (2021) noted that the vast majority of BIM-based LCA studies were concerned with manual and semi-automatic methods to reduce manual inputs and facilitate the LCA process. However, the focus has recently shifted towards automated data exchange. They then identified three integration approaches. The first is the conventional approach, whereby practitioners manually extract BIM and environmental data before conducting the LCA calculation mostly in a spreadsheet format. The second approach is static in nature, in which a semi-automated process of transforming and integrating data sources is applied without the ability to communicate changes between different models during the development process. The third is a dynamic integration approach, which takes into account the temporal variations between inventory data and BIM model (the data collection and mapping process are nevertheless still manually performed).

3.8 LCA of alternative building construction systems

The construction industry is known for its energy intensity and high carbon emissions (Liu et al. 2019). However, alternative construction systems (e.g., prefabrication, modular construction, and 3D printing) can help to reduce the environmental impact of buildings in the pre-use stage. Table 5 describes the construction system being evaluated, building materials used, dimensions of sustainability being considered, and the main findings of the study. The use of prefabricated building components lowers carbon emissions and reduces environmental impacts when compared to the cast-in-place method (Du et al. 2019; Hao et al. 2020; Lip et al. 2020; Yao et al. 2020). Yao et al. (2020) applied a monetization approach to facilitate the comparison between environmental and social factors. It was found that the assembly stage has the highest environmental impact, and that the key contributors are energy and fuel consumption, noise pollution, and the loss of components and materials. Other researchers have considered the environmental benefits of using a prefabricated building envelope (Göswein et al. 2020; Zhang et al. 2020b). The performance of a modular building envelope depends on the materials selection, module design, and the availability of the products within an acceptable distance to minimize the impact of transportation (Göswein et al. 2020). Furthermore, the production of

Table 4 LCA studies of renewable energy systems for buildings

References	On-site energy production	Storage	Technology used	Location relative to building	Findings
(Anctil et al. 2020)	√	-	The application of transparent PV	Window and skylight	The solution Reduces energy use
(Gouveia et al. 2020)	√	√	PV-battery-integrated system	-	Less environmental impacts given on-site energy production and components of the battery are recycled or reused
(Grazieschi et al. 2020)	√	√	PV-battery-integrated system	Roof	Low-energy design outperforms the net zero energy building approach
(Kouloumpis et al. 2020)	√	-	PV	Roof	From environmental perspective, the performance of roof mounted PV vs commercial PV farm is scenario dependent. Commercial farm performs better that roof mounted PV panels, but the opposite is true when long distance transmission is required
(H. Li et al. 2020)	√	-	Ground source heat pump (GSHP)	-	Two types of GSHP: ASGSHP and VGSHP were assessed. From environmental point of view, AGSHP causes less environmental impacts
(Lozano-Miralles et al. 2020)	√	-	Heat pump, biomass boiler	-	Bothe systems have similar impacts, with biomass boiler causing more impact during manufacturing
(Marinelli et al. 2020)	√	-	Dual source heat pump	-	Most of the impacts occur during the use phase (i.e., electric energy consumption)
(Martinopoulos 2020)	√	-	PV	Roof	The environmental benefits of a rooftop PV system are dependent on local electricity mix and installation location. The payback period is mostly estimated at 11 years
(Mehrtash et al. 2020)	√	√	PV-battery-integrated system	Roof	The study developed an optimization model for optimal PV-battery sizing
(Mendecka et al. 2020)	√	√	Stand-alone power plant	-	The environmental impacts of manufacturing and use stage are driven by the location of the building
(Ni et al. 2020)	-	√	Aquifer thermal energy storage and in situ bioremediation	-	The environmental impacts of the proposed system are less by a factor of two compared to the conventional heating and cooling system
(Rossi et al. 2020a)	√	√	PV-battery-integrated system	-	The study focused on environmental and economic optimal configuration of solar systems
(Rossi et al. 2020b)	√	√	PV-battery-integrated system	-	The study compared different battery technologies for residential application
(Sutman et al. 2020)	√	-	Energy piles	-	Energy piles can meet the demands of cooling/heating and reduce the environmental impacts
(Yan et al. 2021)	√	√	Distributed energy system (DES)	-	The use of DES can reduce the environmental impacts, but has a greater cost compared to the conventional energy systems

Table 4 (continued)

References	On-site energy production	Storage	Technology used	Location relative to building	Findings
(Bachmann et al. 2019)	√	-	Fuel cell micro combined heat and power (FC-µCHP)	-	When compared to gas boiler and heat pump, FC-µCHP has less environmental impacts
(Bonamente and Aquino 2019)	√	√	Ground source heat pump (GSHP)-PCM	-	Adding PCM to the system could improve the system performance and reduce the storage volume
(Carvalho et al. 2019)	√	-	PV roof tiles	Roof	Traditional PV is environmentally superior
(Chatzisideris et al. 2019)	√	√	PV-battery-integrated system	-	Environmental benefits of the integrated system are highly dependent on grid mix and battery storage
(Cusenza et al. 2019)	√	√	PV-battery-integrated system	Roof	The study examined the reuse of retired batteries from electric vehicles for residential energy system application
(Gagliano et al. 2019)	√	-	Solar thermal façade	Building envelope	The solution is appropriate for domestic hot water production from environmental and economic perspectives
(Fouad et al. 2019)	√	-	PV	Window-mounted	The production phase along with recycling and glass recovery account for most of the emissions. Recycling and recovery are superior to landfill from an environmental perspective
(Ioakimidis et al. 2019)	√	√	PV-battery-integrated system	-	The secondary use of EV batteries has a significant environmental gain compared to a new battery for building application
(Irshad et al. 2019)	√	√	PV-battery-integrated system	Wall	The use of a PV system for indoor cooling purposes reduces CO_2 emissions by a factor of two, but has a longer payback period compared to a grid-connected air-cooling system
(Stolz et al. 2019)	√	√	PV-battery-integrated system	-	A PV-battery system results in a notable reduction in GHG emissions compared to electricity from the grid
(Tevis et al. 2019)	√	√	Grid only, PV, and PV-storage systems	-	PV panels reduce dependence on the power grid but increase metal depletion
(Teah et al. 2019)	√	-	PV	-	Produces 31% of required electricity, reduces GHG emissions by 27%

Table 5 LCA application for evaluating alternative construction systems

References	Construction system	Building material	Environmental LCA	Economic considerations	Outcomes
(Balasbaneh and Ramli 2020)	Prefabricated modules	Steel vs. concrete	√	√	Overall, steel shows better performance in terms of environmental and economic factors
(Göswein et al. 2020)	Prefabricated envelope	Composite system	√	-	Environmental performance of modular construction depends on material selection, module design, and the availability of the products within an acceptable distance to minimize the impact of transportation
(Hao et al. 2020)	Prefabricated building components (e.g., stairs, wall, beams)	Steel and concrete	√	-	A 15% reduction in carbon emissions compared to the conventional cast-in-place method
(Heravi et al. 2020)	Prefabricated frames	Steel	√	-	An anticipated reduction in carbon emissions and energy use by 4.4% and 9.2% respectively
(Kong et al. 2020)	Prefabricated slab	Concrete	√	-	Significant reduction in carbon emissions by nearly 35% compared to the cast-in-situ method
(Li and Zheng 2020)	Prefabricated concrete piles	Concrete	√	√	A linear relationship was found between the construction stage carbon emissions and the area, number, and cost of pile foundations
(Lip et al. 2020)	Prefabricated concrete structures	Concrete	√	-	Overall, the carbon footprint of prefabricated structures is lower than that of cast-in-place structures
(Pujadas-Gispert et al. 2020)	Prefabricated concrete deep foundations	Concrete	√	√	The use of prefabricated deep foundations results in a reduction in most impact categories, but the prefabrication method incurred higher construction cost (12–37% increase)
(Yao et al. 2020)	Prefabricated building components	Concrete	√	√	The assembly stage has the highest environmental impact. The key contributors are energy and fuel consumption, noise pollution, and the loss of components and materials
(Zhang et al. 2020b)	Prefabricated façade	Concrete	√	√	The production of prefabricated concrete elements (PCEs) with recycled construction and demolition wastes lowers GHG emissions and cost compared to PCE produced with virgin material
(Agustí-Juan et al. 2019)	Digitally fabricated building elements	Mainly wood and concrete	√	-	Digital fabrication techniques can provide environmental benefits and material efficiency during production; however, the use of hybrid materials in multi-functional architectural elements could negatively impact material recyclability
(Dara et al. 2019)	Modular homes—repurposed shipping containers	Steel	√	√	The environmental impacts of homes made with repurposed steel containers differ by 3% compared to wood-based homes

Table 5 (continued)

References	Construction system	Building material	Environmental LCA	Economic considerations	Outcomes
(Du et al. 2019)	Prefabricated building components (stair, slabs, beams, etc.)	Concrete	√	-	Prefabricated buildings have less environmental impacts compared to cast-in-place buildings, by nearly 18%
(Kamali et al. 2019)	Modular construction	Wood	√	-	Modular construction is not always the optimal choice and practitioners must consider design optimization, material waste reduction, and transportation needs to improve the viability of this choice

prefabricated concrete elements (PCE) with recycled construction and demolition wastes lowers GHG emissions and costs compared to PCE produced with virgin material (Zhang et al. 2020b).

3.9 LCA inventory (static vs. dynamic)

A core design parameter of LCA methodology is the development of the life cycle inventory, which refers to the collection of data related to inputs and outputs of a particular product system. There are two main categories of data. Primary data, which LCA practitioners collect themselves, and secondary data, where the data are drawn from generic databases or literature. Silva et al. (2020) found the limited adoption of LCA is due to the amount of data needed to establish LCIs. The authors proposed that primary data collection should be prioritized to foreground processes because they account for most of environmental burdens of construction products, while background processes can depend on existing databases. Furthermore, the environmental impacts of building materials and products are quantified using pre-calculated coefficients from existing databases, which are frequently criticized for being inconsistent and incomplete (Crawford et al. 2019). Instead, Crawford et al. (2019) proposed a hybrid method that combines data from the process-based approach with economic input–output data that will generate a more comprehensive and accurate LCI.

Furthermore, to provide an accurate environmental assessment, it is vital to build regionalized databases that reflect real-world scenarios. In this regard, Alzard et al. (2020) claimed that creating a representative LCI dataset for the production of recycled concrete aggregates in a UAE city enabled stakeholders to make informed decisions about whether recycled aggregates are a more environmentally friendly option. Ayagapin and Praene (2020) showed that environmental costs significantly differ depending on a number of factors, such as sources of construction materials, transportation method, electricity mix, and geographical location, which indicates the importance of regionalized databases. Moreover, another approach to provide representative and accessible environmental information of building products is developing Environmental Product Declarations (EPDs). These have emerged as a major tool in environmental assessment policies in developed countries driven by the widespread adoption by several environmental certification systems, regulatory requirements, and environmental assessment tools (Arvizu-Piña et al. 2020).

Data granularity also affects LCA results because the results of some impact categories are strongly related to data resolutions (Karl et al. 2019). In addition, granular data can generate more accurate LCA results (Mayer and Bechthold 2020). The use of real-time data is crucial to the accuracy and reliability of LCA results thanks to the dynamic nature of buildings. Vuarnoz et al. (2020) demonstrated how real-time data of occupancy profiles and appliance usage patterns can be used to improve the accuracy of LCA results. Examples of common real-time data sources include smart utility meters (Vuarnoz et al. 2020), IoT for occupancy detection and appliance use (Mercader-Moyano et al. 2020; Shittu et al. 2020), and sensors to measure indoor temperature and relative humidity.

3.10 Development of LCA tools

Several proprietary and open source LCA tools have been developed to support LCA application, such as OpenLCA, SimaPro, and GaBi. However, the limited adoption of LCA for buildings can be attributed to the complexity of buildings and the amount of data required to establish LCIs (Silva et al. 2020); hence, various specialized LCA tools have been developed to facilitate LCA practice in the building sector. Building LCA tools can be in the form of stand-alone software, such as Athena Impact Estimator or in the form of a plug-in, such as Tally and One Click LCA. Although existing tools can simplify LCA calculation, they are viewed as a black box since the end users have little knowledge about the assumptions and internal workings of the tool (Bueno and Fabricio 2018). This can preclude a thorough understanding of the LCA results and environmental hotspots (Al-Ghamdi and Bilec 2017). Furthermore, different LCA tools can generate inconsistent results for the same design problem because each tool utilizes various workflows and databases (Mora et al. 2020), as well as the omission of some processes, such as construction (Nizam et al. 2018). For a more detailed discussion of the limitations and challenges of buildings LCA tools, the reader is referred to the following recent reviews (Mora et al. 2020; Obrecht et al. 2020).

Apart from existing commercial LCA tools, researchers have developed solutions to address specific aspects related to building LCA. Domjan et al. (2020) developed an Excel-based LCA tool to evaluate operational energy use and embodied emissions. Miyamoto et al. (2019) developed a decision support tool to integrate LCA and life cycle cost during the early-design stage for dwellings. To reduce the time required to compare design alternatives, Duprez et al. (2019) created machine learning models that allow designers to rapidly evaluate new alternatives using the trained models. Several studies have attempted to improve data exchange and mapping between various data sources, including BIM, generic LCA databases, and EPDs. Nizam et al. (2018) developed a Revit plug-in tool to estimate the embodied energy of materials, construction, and transportation by connecting information from BIM to a customized database containing embodied energy coefficients. Similarly, Jalaei et al. (2020) built a plug-in that enables data mapping between a designated dataset from the Ecoinvent database and the extracted materials from the building model. The main advantage of these customizable tools is the ability to incorporate data from various external sources that commercial tools, such as Tally, do not allow (Forth et al. 2019). Nevertheless, further research is required to establish a permanent bidirectional link between building models and environmental databases in order to improve the exchange of data, exploration of what-if scenarios, and optimization of design and operational parameters.

4 Gaps and limitations in current LCA research

This review of the current LCA research landscape has identified several gaps and limitations, which will be described in this section.

4.1 Lack of alignment with domain models and manufacturing systems

There is a growing interest in BIM-LCA integration. Nearly 20% of the analyzed studies have used BIM, including using BIM as a source of data, a parametric model for energy consumption/simulation, and as a simplified calculation tool for LCA by embedding environmental data into BIM objects. The most prevalent use of BIM in LCA applications is for geometric and material data acquisition. A similar finding was demonstrated in Obrecht et al. (2020), where it was found that exchange of information is the most common link between BIM and LCA tools. However, this is currently limited by semantic incompleteness and interoperability issues between current software solutions. Soust-Verdaguer et al. (2017) demonstrated that the BIM environment is missing critical aspects that are important for environmental impact assessment, such as temporal processes, refurbishment and maintenance information, end-of-life treatment scenarios, and recycling data. Apart from the limitations in semantic information, automatic mapping of BIM data and LCA resources to facilitate the process of life cycle inventory building and resolve the interoperability issue is lacking. In addition, building components and systems are produced through a manufacturing process. While the embodied carbon of materials forming the final product is often fully considered, these manufacturing systems tend to not factor in the design configuration that is best conveyed via a BIM. In fact, automation of the building production necessitates exploitation of information models (i.e., BIMs) in each phase of the design, construction, and operation management life cycle. Current applications of BIM on projects mainly involve design information but often lack as-built and operation management information. Product manufacturers have recently engaged with BIM by making their manufactured products BIM compliant to enable designers to import virtual products specification into their design environment, which provides a means to assessing the environmental impact of their interventions.

4.2 Lack of reasoning and decision support capability

Buildings involve a wide range of materials, products, and actors interacting in a dynamic and non-linear workflow as part of a complex ecosystem over the building's lifetime. Furthermore, there are many life cycle variations that LCA tools and methods must take into consideration, including building usage, energy supply, changes in the energy mix, and occupancy patterns. Hence, minimizing the environmental burden of buildings requires a comprehensive approach that factors in the complexity and the dynamic nature of building LCA. This requires the exploration of various scenarios for the evaluation of alternative design options, renovation strategies, and the generation of actionable improvement for building operations. In this context, existing literature on decision support tools shows limitations in the proposed solutions, both in terms of scope and capabilities.

4.3 Limited efforts to scale up LCA from buildings to district level

Literature related to the LCA of buildings at an aggregated level is scarce and has a multitude of heterogenous methodological approaches (Lotteau et al. 2015). There are two main approaches for building stock modeling, namely a top-down approach that relies on some macro-economic indicators and a bottom-up approach that clusters buildings based on common characteristics (Mastrucci et al. 2017). In this review, it was found that the majority of studies focus on applying LCA on individual buildings or a group of buildings with a complete background information about each building. Several studies have considered large-scale LCA applications for a variety of purposes, such as renovation of existing housing stocks (Österbring et al. 2019), energy-saving scenarios for EU-wide housing stock (Allacker et al. 2019), and understanding the level of details required to conduct LCA at a large scale. The main challenge of scaling up LCA applications can be seen as a trade-off between the cost of collecting data and the reliability of LCA results. To deliver reliable and sound LCA results at district and city-wide level, it is critical to understand the level of detail required at the building level and also the informative attributes at the district level. It is worth noting that a number of projects funded under the Horizon 2020 Smart Cities and Communities program are progressing the concept of Positive Energy Districts. These projects consider four dimensions in their district interventions, namely: energy efficiency, mobility, information and communication technologies, and citizen engagement. However, these projects fall short in embracing the LCA philosophy.

4.4 Lack of support of temporal information

There is a need to factor in temporal information in the background and foreground life cycle inventory and impact assessment methods to address maintenance, operation, deconstruction, and end-of-life treatment (Anand and Amor 2017; Cardellini et al. 2018; Tiruta-Barna et al. 2016). Construction processes involve longer time scales that in other industries (Bueno et al. 2016; Soust-Verdaguer et al. 2017). Therefore, the consideration of the time dimensions in product system modeling is essential to understand the resulting pollutant emissions and resource consumption (Anand and Amor 2017; Bueno et al. 2016; Skaar and Jørgensen 2013). However, a limited number of studies have tested the use of dynamic data during construction and operation stages (11 studies only). The main type of real-time data is concerned with electricity consumption but some studies have used IoT devices for occupancy detection appliance use or have developed sensors to measure indoor temperature and relative humidity. Nonetheless, further research is needed to determine the impact of accessing dynamic data and the frequency of data collection on assessment accuracy.

4.5 Limited consideration of health and well-being

Traditional LCA typically only considers the impact of outdoor emissions on human health, while ignoring the impact of indoor pollutants. Currently, stakeholders and existing commercial building assessment schemes (e.g., LEED and BREEAM) are often concerned with the toxicological impacts on inhabitants during the building design stage and in the selection of construction products (Kalberlah et al. 2019). During the use stage, assessment of health impacts associated with exposure to toxic contents of building material is limited by data availability and lack of modeling capability (Huang et al. 2019). However, research shows that indoor emissions during use stage have a considerable impact on the health and well-being of a building's occupants (Skaar and Jørgensen 2013). Factoring in people's health and well-being during the design and operation of buildings can significantly influence the decision-making process (Tao et al. 2020). For example, the trade-off between indoor thermal comfort and environmental impacts during the design stage can reduce the number of design alternatives (Wang et al. 2020); the impacts on human health from indoor air contaminants influence the selection of building material (Khoshnava et al. 2020); and, achieving lower GHG emissions through alternative building designs (e.g., wood-based buildings) has an impact on thermal comfort (Grygierek et al. 2020). During building operation, Hoxha et al. (2020) developed a user-centric approach and showed that space densification (i.e., increasing the number of people occupying a space) could potentially reduce the overall environmental impact, while maintaining an acceptable comfort level. Although this review has identified several studies that have considered the health and well-being of building occupants, further research is needed to dynamically measure indoor emissions. Moreover, the influence of occupant behaviors on the concentration of indoor emissions (e.g., window opening/closing) must be integrated with LCA modeling to accurately assess the long- and short-term impacts of indoor emissions on health and well-being.

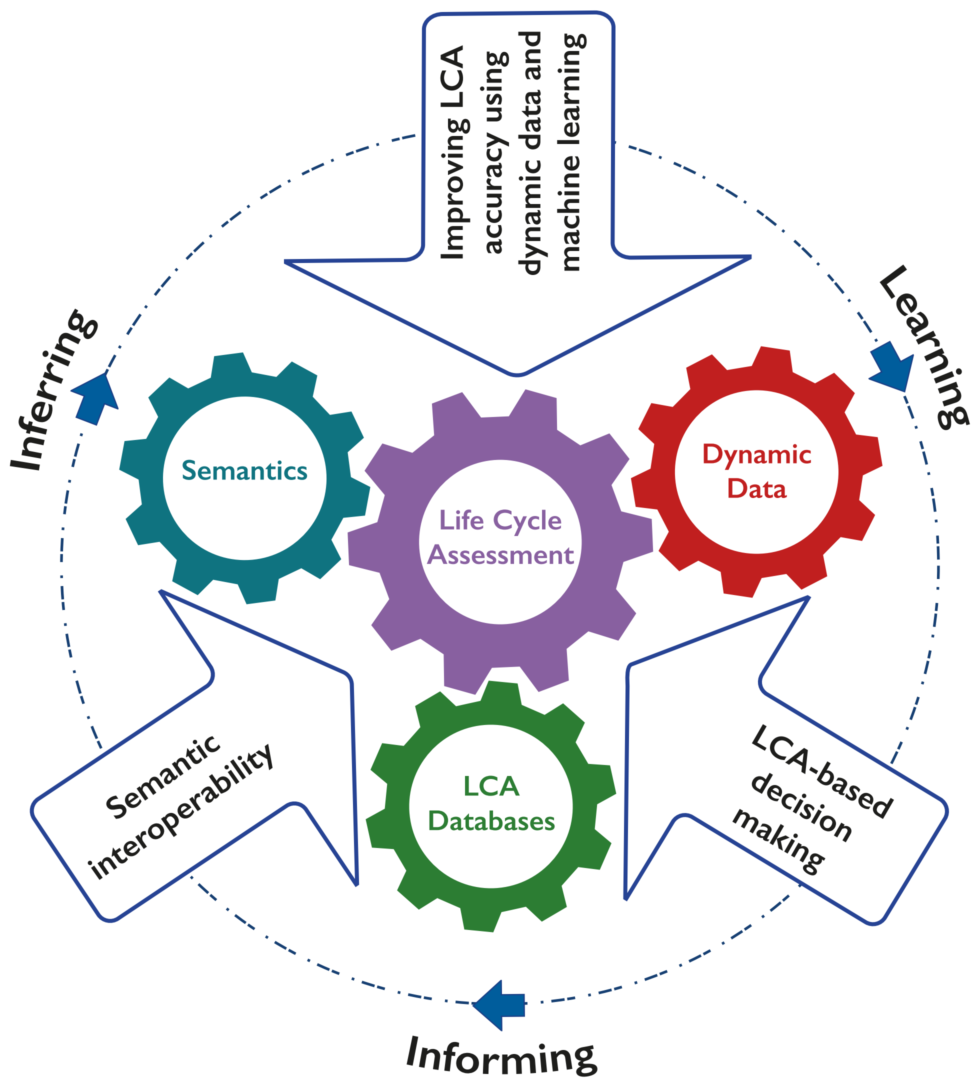
5 LCA: Directions for future research

There are three recurring themes in the gaps identified in the earlier section, namely semantics, temporality (i.e., dynamic data), and intelligence (to support decision making) as illustrated in Fig. 5. These themes are applicable across the life cycle of a building, from concept design to end-of-life. We therefore start by elaborating on each of these themes before discussing some of the ways in which these apply to each life cycle stage.

5.1 Key recurring themes for future research in LCA

LCA underpinned by semantics and informed by dynamic data can pave the way to a more accurate LCIA, while supporting decision-making and active control of buildings and districts. As such, there is a need to pave the way to a (near) real-time LCA capability that exploits a wide range of digital resources and which leverages intelligence (in the form of

Fig. 5 Key recurring themes in future LCA research applied to buildings



machine learning and optimization algorithms) to assess the whole life cycle environmental impacts of buildings.

5.1.1 Semantic interoperability for LCA

By semantics, we mean the reliance on computer-based models that provide a formal description of the context that underpins the domain under investigation (Gruber 1995). In practice, the domain conceptualizations held by stakeholders and software across disciplines tend to be incompatible and necessitate ad-hoc solutions (e.g., mappings and alignments) to overcome semantic heterogeneity (Howell et al. 2017). The use of semantics, including BIM and GIS, provides a means to integrate and contextualize existing inventory databases, and provides a sound basis to streamline the LCA process of buildings and districts. This will require an inventory of existing LCA databases, methods, standards, and tools to be established. In addition, their underpinning semantics should be elicited. Furthermore, the existing relevant semantic models, such as BIM and GIS, and current LCA databases should be expanded to address the completeness requirements necessary to provide holistic accounts of environmental impacts of buildings and wider districts. Key methodological challenges in delivering semantic LCA require a comprehensive (life cycle and supply chain) understanding of the semantic resources needed to deliver life cycle assessment at building and district level. A reference architecture for semantic LCA that factors in existing databases, models, methods, and tools is also required. Finally, a consensus and requirements of semantic and dynamic LCA should be developed.

5.1.2 LCA based on dynamic data

Research is needed to assess the impact of utilizing dynamic data on the accuracy of LCA results throughout different project stages, such as construction and operation. Delivering real-time accounts of life cycle performance of buildings and districts using multi-aspect sensory data, including (a) indoor and outdoor environmental data and (b) building and district performance data such as energy consumption, pollution, and carbon emissions. The collection of dynamic data will require identification of necessary instrumentation and data capture technologies while leveraging existing building management system and information and communication technology (ICT) infrastructure. This requires a context to sensed data to be provided via semantics. In addition, a systems approach should be adopted, whereby the performance and environmental impact of physical artifacts, such as a building, involves the assessment of each constituent subsystem.

5.1.3 Machine learning–based decision making

Research is needed to evaluate the impact of semantic and dynamic LCA in the decision-making process by non-experts, which should explore a wide range of options and scenarios with the least environmental impacts, while advising on corrective measures through actionable machine learning. Machine learning techniques, including model predictive control and optimization algorithms, can be used to deliver actionable knowledge to inform various control strategies and corrective actions with a view to reducing the gap between predicted and actual environmental impacts. These may also be used to overcome data gaps for LCA. Machine learning technologies may also be used in real-time applications to monitor and control the systems in a way that reduces negative environmental impacts. Machine learning models may be more easily integrated than other black box methods because they are more easily interpreted by the users. However, the monetary and time costs of establishing machine-learning models should be considered for real-time use.

5.2 LCA: research directions across life cycle stages

This section will discuss some of the ways in which the recurring themes that have been identified in this paper (i.e., semantics, temporality, and intelligence) apply to each key life cycle stage of a building.

5.2.1 LCA in design

There is an increasing demand for LCA modeling approaches that can be initiated during the early-design stage and which can factor in uncertainty, including dealing with incomplete, unreliable, and unascertained information (He et al. 2018). As elaborated earlier in this paper, there are three forms of uncertainty, namely stochastic uncertainty, choice uncertainty, and lack of knowledge of the planned and projected building within its environment across the life cycle and supply chain (EC-JRC 2010). Conversely, engineering systems involve three types of uncertainty, namely model uncertainty, scenario uncertainty, and parameter uncertainty (Zhang et al. 2020a). This notion of uncertainty is compounded by the fact that a building involves a dynamic and multi-faceted reality that is conveyed to us through multi-aspects sensory data, which is enabled by our increasingly connected world. This necessitates the need to confer a dynamic dimension to LCA, as reflected in consumption data, inventory datasets, characterization factors, and weighting factors (Su et al. 2019a). Material and product selection at an early-design stage must be informed by environmental, social, and economic considerations (Hertwich et al. 2019). The end-of-life dimension of these products should be planned as early as the briefing and concept design stage. However, existing databases (e.g., Ecoinvent) are incompatible with end-of-life treatment of both methods (Mirzaie et al. 2020). As such, there is a need to (a) embed LCA methods into the early-design process and underpinning workflow enabled by a seamless BIM-LCA integration; (b) promote comparative approaches that consider multiple environmental, economic, and social indicators to identify the design alternative with the lowest environmental impacts; (c) integrate LCA with computational and analytical techniques, such as machine learning, that can deal with uncertainty; and (d) provide a means of predicting operational carbon emissions during the early-design stages. Research is also needed to explore and promote the acceptance of an LCA philosophy by designers and practitioners, as well as the adoption of the underpinning methods. Evidence suggests that the limited adoption of LCA can be attributed to a wide range of factors, including the amount of data and time needed to establish LCIs (Silva et al. 2020).

5.2.2 LCA in retrofit and construction

Research into using alternative construction systems (e.g., prefabrication, modular construction, and 3D printing) may provide a means to reduce the environmental impact during the construction phase. It has been noted that a circular economy approach (i.e., design, use, reuse, and recycle) contrasts with the linear value chain model used in the building construction industry (de Wolf et al. 2020), and is hindered by several structural barriers (Futas et al. 2019). This is exemplified by the management of waste in the industry. Research is needed into approaches that promote decarbonization and waste elimination in construction, which involves the complex supply chain that gravitates around a construction site.

Conversely, the large existing building stock in Europe and beyond needs to undergo a program of rehabilitation and retrofitting. As noted earlier, non-energy-related rehabilitation measures tend to be ignored, while the focus remains on improvement to the building envelope, energy system, and energy end-use (Thibodeau et al. 2019). Therefore, holistic (i.e., system engineering) retrofitting approaches, rooted in an LCA philosophy, informed by decision support systems (including machine learning and optimization algorithms) should be promoted. Applications involve selecting the most efficient renovation and/or retrofitting measure under a given environmental and economic context. Some further applications are listed in Table 3. Conversely, the selection of a construction (including structural) system should undergo a similar approach informed by decision support systems. Future research should explore ways of (a) ensuring a semantic continuum between design and construction stages in a way that ensures seamless data and information transfer from design to construction; (b) leveraging on digital twinning initiatives to minimize errors and rework during the construction stage (Boje et al. 2020); and (c) promoting the use of decision support systems to devise optimal intervention strategies with the least environmental impacts, relying on real-time sensory data and site information.

5.2.3 LCA in operation stage

Current approaches to LCA do not consistently factor in (in the foreground and background inventory systems) life cycle variations in (a) building usage, (b) energy supply (including from renewable sources), and (c) building and environmental regulations, as well as other changes over the building/district lifetime. These include (a) change in the energy mix of a building/district or upgrading/retrofitting the energy system(s) in place and (b) time increase of energy demand during the lifetime of a building due to a wide range of reasons, including changes in occupancy patterns. In this context, the key limitations and challenges faced by current LCA methods and tools include site-specific considerations (Bueno et al. 2016), several local impacts need to be considered in building assessments, such as the microclimate; (b) model complexity (Anand and Amor 2017), buildings involve a wide range of material/products, interacting as part of a complex assembly or system; (c) scenario uncertainty (Anand and Amor 2017; Bueno et al. 2016), the long use phase of buildings, including the potential for future renovation, poses uncertainty problems in LCA currently not addressed; (d) health and well-being (Bueno et al. 2016; Skaar and Jørgensen 2013), traditional LCA methodologies do not address indoor and outdoor environmental impacts on health and well-being; and (e) lack of consideration for social and economic aspects (Anand and Amor 2017; Negishi et al. 2018).

Operational energy use in buildings has attracted increasing research, as evidenced earlier in (Gardezi and Shafiq 2019; González-Prieto et al. 2020). In fact, we have in recent decades witnessed the proliferation of distributed energy resources (DERs), management structures, and ICT concepts, which pave the way to a diverse smart grid of interconnected systems, agents, and domains (Howell et al. 2017). Given this marked increase of DER penetration, technologies such as microgrids, virtual power plants, energy hubs, and demand side management are being deployed within buildings and districts, including in the context of energy retrofitting initiatives. As the density of DERs and DER management structures increases, the potential benefit from coordination across these structures and the challenges associated with their integration with the grid increase dramatically (Howell et al. 2017). In this context, LCA research is needed to factor in these technology evolutions, whereby diverse and distributed energy systems are dynamically interoperated through ICT penetration to achieve demand response scenarios and local energy balancing, while promoting the adoption of clean energy.

5.2.4 LCA in end-of-life

The recycling stage of a building is attracting increased research, fueled by the need to promote circularity principles. There is even a growing trend to use the "cradle-to-grave-to-reincarnation" concept in the recent literature. However, as argued earlier, an efficient recycling strategy should be embedded during the early concept design stage of a building. It is interesting to note that existing databases (e.g., Ecoinvent) are incompatible with the end-of-life treatment of the widely used LCA methods, including PEF and CEN EN 15804/15978 (Mirzaie et al. 2020). As such, future research should (a) enhance existing LCI databases to embed end-of-life data and information; (b) promote comparative approaches that consider multiple environmental, economic, and social indicators to identify the optimal material selection and design alternative with the highest recycling potential; and (c) promote the use of semantics and digital twins of buildings to facilitate the dismantling and reuse of building parts.

6 Conclusion

This study presents a review of the research progress in the field of building LCA, focusing on the current applications of LCA in buildings. The review followed a use case-based approach to further investigate each identified use case to its full extent. In addition, this paper has identified several directions for future research based on the highlighted gaps and limitations of the most recent publications.

There is an increasing adoption of building LCA across the life cycle stages of a building, including manufacturing of building materials, design, construction, use phase, and end-of-life. However, successful LCA implementation must factor in the dynamic nature of buildings, variable operational and environmental conditions, long time scale of buildings, in addition to the specific challenges associated with each life cycle stage. During early-design stages, conducting LCA is challenging as evaluating design alternatives is computationally expensive coupled with design choice uncertainty and a lack of detailed information. Also, these challenges are exacerbated by the need to promote circular economy principles and alternative construction systems to minimize the environmental impacts originated from construction processes and construction waste. While conducting a large scale LCA, such as evaluating retrofit proposals of existing building stock, it is vital to acknowledge the trade-off between the reliability of the LCA results and the cost of collecting relevant data. Challenges associated with LCA in the operational stage stem from several factors, including a variation in operational energy demand, energy system evolutions, building use/occupancy patterns, and building and environmental regulations. Furthermore, this study has highlighted the importance of addressing the temporal and spatial dimensions associated with LCI by developing regionalized databases and dynamic data to enhance the accuracy of LCA results.

While all previous efforts have led to incremental progress, this paper promotes the concept of semantics to integrate and contextualize existing domain models (e.g., BIM), LCA tools, and inventory databases to streamline the LCA process and provide holistic accounts of environmental impacts of buildings and districts. Also, the paper argues the need to develop decision-support systems that leverage dynamic data, machine learning, and optimization methods for real-time assessment of design options, monitoring, optimization, and control of buildings.

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Declarations

Conflict of interest The authors declare no competing interests.

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