Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments

Roberto Minunno a,∗, Timothy O’Grady a, Gregory M. Morrison a, Richard L. Gruner b

a Curtin University Sustainability Policy (CUSP) Institute, Curtin University, Kent Street, Bentley, 6102, WA, Australia
b The University of Western Australia, 35 Stirling Highway, Crawley, 6009, WA, Australia

ARTICLE INFO

Keywords:
Life cycle assessment
Buildings
Embodied energy
Embodied carbon
Construction material
Meta-analysis
Systematic literature review

ABSTRACT

Life cycle assessment is a tool to quantify the environmental impact of products and has been widely studied in the building context. This is an important context given the building sector’s substantial embodied energy and carbon. Against this backdrop, this study has two main objectives. The first objective is to create a benchmark the environmental impact of buildings. The second objective is to develop a procedural guideline that assists practitioners in decreasing the environmental impact of buildings. To achieve these objectives, a systematic review of the relevant literature was conducted to categorize and summarize relevant studies. A meta-analysis followed to synthesize the life cycle assessment results that emerged from the collected articles. The articles were categorized into two main groups: articles on construction materials and articles on entire buildings. Eight construction materials (i.e., concrete, reinforcement bars, structural steel, timber, tiles, insulation, and plaster) and three building types (i.e., concrete, timber, and steel) were identified, and related embodied energy and carbon were extracted. Subsequently, the data were analyzed through descriptive and inferential statistics. Findings from the meta-analysis informed a regression model, which in turn informed a procedural guideline for practitioners who seek to reduce buildings’ environmental impact. Further, the findings of this paper shed light on previously equivocal results concerning the impact of construction materials and buildings, but also support previous findings for structural materials, showing, for example, that the use of timber structures results in substantial savings over concrete structures in terms of both embodied energy (43%) and carbon (68%).

1. Introduction

Globally, 60% of raw materials, by mass, are used in the building sector [1], which embodies 6% of global energy use and releases 11% of related carbon dioxide into the atmosphere [2–4]. During construction, operation and demolition stages, materials such as concrete, steel and timber are produced and discarded [5], which increases material depletion and pressure on landfill [6]. In an attempt to measure and decrease this environmental impact of buildings, the life cycle assessment (LCA) tool has gained considerable traction [7]. Applying LCA to the construction industry can help quantify and reduce the adverse impact that materials and components have on various environmental impact indicators, including the embodied energy and carbon emissions of buildings [8].

In the main, extant LCA studies have failed to provide a consistent picture with LCA results on the embodied energy and carbon of construction materials varying substantially between them. For example, while some authors show that the recycling of concrete allows material saving (e.g., Blengini [9] and Visintin et al. [10]), others demonstrate that the use of steel yields a greater decrease in terms of embodied energy compared to concrete structures [7,11,12]. Additionally, to the best of the authors’ knowledge, a quantitative integration between end of life practices and related savings of the environmental impact of buildings is lacking. Consequently, many LCA scholars and practitioners are confused about measuring, verifying, and comparing LCA results [13]. Further, LCA practitioners might be uncertain about the most beneficial effects of strategies to reduce buildings’ environmental impact. LCA practitioners could solve this issue by investing more time and effort into collecting data, carrying out sensitivity analyses and creating LCA comparative scenarios [12,14]. However, since LCAs are complex, time consuming and data hungry procedures, practitioners often prefer to avoid these steps and present their results as mere point estimates rather than relative metrics [15]. Therefore, without relative metrics providing comparative interval values, even when LCA results are presented, they only provide a partial picture of practices’ environmental impact [16].
In view of the above, this article addresses three key research gaps and challenges (previously also identified by Anand and Amor [17] in their seminal work on the LCA of buildings). Specifically, the first gap addressed here is the absence of a collection of LCA results into a comprehensive benchmark. The second gap is the lack of guidelines that allow LCA practitioners to compare their results on the environmental impact of buildings. Finally, the third gap is the lack of guidance on selecting a functional unit for reporting and comparing LCA results.

To address these gaps, a systematic literature review (SLR) was combined with a meta-analysis method to collect and analyze the LCAs of construction materials and buildings. The SLR is a structured approach for the collection, selection and review of the literature on a predefined scientific topic – in the analyzed case, the LCA of construction materials and entire buildings [18,19]. Then, a meta-analysis was adopted to aggregate the quantitative results extracted from the collected studies [20,21]. This aggregation was critical because meta-analyses zoom out over the diversities of study methods and results, and, in taking into account these diversities, can help resolve inconsistencies and provide further guidance to LCAs.

Consistent with SLR guidelines (e.g., Littell et al. [21]), the author team followed essential reviewing and coding steps adapted to the context of LCAs, and extracted the relevant data and analyzed them through descriptive and inferential statistical tools. Within the collected 181 studies, eight were identified as the most used construction materials: concrete, reinforcement bars, structural steel, timber, tiles, bricks, insulation, and plaster; and three building structure materials: concrete, timber, and steel. Once the studies were categorized between construction materials and entire building structures, their results in terms of embodied energy and carbon were extracted. The analysis was completed with a summary of the most common end of life alternatives.

This review article pursues a number of key research objectives. The first objective is to create a benchmark of embodied energy and carbon of construction materials and building. The second objective is to employ this benchmark in producing an evidence-based procedural guideline that can assist LCAs in comparing and diminishing the negative environmental impact of buildings. The SLR and meta-analysis employed result in a comprehensive collection representative of the range of results for related LCAs to date. The collected results were then analyzed through descriptive and inferential statistical tools (e.g., box-whisker charts, regression lines) to create benchmarks of eight construction materials (i.e., concrete, reinforcement bars, structural steel, timber, bricks, tiles, insulation (EPS) and plaster) and three structural materials (i.e., concrete, timber and steel). The analyzed data were then employed to create a two-step procedural guideline designed to help LCA practitioners to rank and improve their LCA results. By providing a benchmark of the embodied energy and carbon of construction materials and buildings, the first step assists practitioners in ranking and comparing their preliminary LCA results with the benchmark in this paper. This benchmark helps practitioners in ranking and comparing their results with the results obtained in the identified LCA studies. The second step guides LCA practitioners to select and adopt several strategies that were collected from the literature aimed at decreasing buildings’ adverse environmental impact. In short, the guideline can be used to make important design decisions on which materials and strategies to adopt so as to diminish the adverse environmental impact of buildings.

In addition to creating procedural guidelines, this study makes three important theoretical contributions. First, it provides a comprehensive summary of the environmental impact of construction materials and buildings. This summary could be used as databases and inventories for future LCA practitioners and scholars. Second, it explores and resolves contradictory study results associated with the choice of LCAs’ functional unit. The importance of defining the functional unit in LCA is understood but often underestimated. This oversight could, in turn, lead to incorrect conclusions concerning assessments of the environmental impact of buildings. Third, the study uncovered important results for the LCA of structural materials, quantifying the total amount of embodied energy and carbon that can be saved through different strategies. For example, data suggested that using a timber structure instead of concrete results in substantial savings in terms of both embodied energy (43%) and carbon (68%).

2. Methodology

SLRs are widely regarded as a comprehensive, reproducible, and rigorous method to scan, identify and report findings from selected literature [19,22]. As mentioned in the Introduction, this article combines an SLR with a meta-analysis to identify, aggregate and statistically analyze relevant quantitative results [19]. Consistent with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; see Moher et al. [23] and PRISMA Checklist, Appendix A), this SLR unfolds in four main steps, and lays the foundations of a meta-analysis method (see Fig. 1). First, a list of relevant keywords were identified and employed to form the Boolean search string (step 1). The search string was then applied to the most used databases in the field of construction, waste management and environmental sustainability and the data imported into EndNote X9 and Excel v.1908, where the copies were eliminated (step 2), and exclusion criteria were applied to reach the shortlisted articles (step 3). Finally, the shortlisted articles were divided into two main categories: environmental impact of construction materials and impact of entire buildings. This categorization process was followed by an extraction and analysis of the data (step 4). The following sub-sections describes each SLR step in more detail before turning the attention to the in-depth analysis of the result.

Step 1) Keywords and search string determination. The research keywords were determined starting from the research gaps, then combined in the Boolean research string: (life cycle assessment OR LCA) AND (embodied energy OR carbon emissions) AND building. Where keywords were two words, they were included in quotation marks. The search engines automatically search for plural spelling of the same keyword.

Step 2) Database search, data extraction and copies elimination. Then, the search string was applied to four selected databases: ScienceDirect, Scopus, ProQuest and Web of Science, searching in the titles, abstracts or articles’ keywords (search date: January 2021). The search was not limited to year interval, but only to journal articles in English and in the subject area environmental science. This search resulted in 1161 articles, which were then extracted as source metadata into EndNote X9 and Excel v.1908, followed by reducing the number of articles to 618 by eliminating the copies.

Step 3) Articles exclusion and shortlist creation. Exclusion criteria were formulated at this stage to minimize bias, before starting the search.
Two authors independently surveyed the 618 articles and decided to keep or exclude the references. A Cohen’s kappa was calculated to evaluate the level of agreement reached by the two authors (see Section 2.2 for more details) [24]. Some references were excluded from the shortlist when they did not provide enough information on the employed LCA, used incompatible functional units, or could not be retrieved. In this step, the shortlist was reduced from 618 references to 181.

Step 4) Thematic analysis. The 181 shortlisted articles were analyzed according to their thematic focus, which was explored through a thematic analysis of its content. Specifically, articles that were studying the environmental impact of construction materials or LCA of buildings were searched. Three main themes were identified: articles on construction materials (73), articles on entire buildings (100) and articles on strategies and insights (48). The most common construction materials included concrete, reinforcement bars, steel, and timber, while articles on entire buildings quantified the impact of producing building structures or focused their efforts on calculating the environmental footprint of whole buildings (including finishing materials). Finally, 48 articles were included in this literature review as they advise on new materials, provide insights on sustainable waste management strategies, or are included and used across this paper because of their relevant findings. A thematic analysis of the remaining 48 articles that were selected in the SLR process was also conducted. The focus of the thematic analysis was on strategies that have been adopted to diminish buildings’ impact throughout their life cycle. Following established guidelines (e.g. Refs. [25,26]), this analysis consisted of 5 key steps: (1) reading the shortlisted articles, transcribing, and noting initial ideas, (2) framing ideas into initial keywords which evolved into themes and strategies, (3) forming emergent strategies among the collected articles, (4) completing the strategies through consideration of the effectiveness in decreasing the environmental impact of buildings, and (5) integrating the strategies with the proposed procedural guideline. These strategies are presented in Section 4.2.

Once the articles were selected and categorized into themes, relevant data on the environmental impact of construction materials and buildings were extracted as data in Excel, to carry out a meta-analysis. The meta-analysis consisted of descriptive statistics to interpret the data findings and explore correlations between variables (box-whisker plots to visualize the ranges of data and identify outliers), and inferential statistics (correlation and regression patterns between embodied energy and carbon) to compare and investigate relationships between the exported data on the environmental impact of materials and buildings.

In addition to the 181 articles that surfaced through the SLR, 56 more articles were manually selected. These articles were not identified through the above outlined SLR keyword string but proved relevant, nonetheless. For example, Jamieson et al. [27], Kupwade-Patil et al. [28] and Yan et al. [29] were added because the SLR keyword string alone could not source enough information on embodied energy related to integrating by-products into construction materials. Also, Kamali and Hewage [30] and Fenner et al. [15] were manually added as they provide seminal reviews of LCA of buildings. Interested readers can find a complete list of the 56 manually added references in Appendix B.

2.1. Life cycle stages and research boundaries

The LCA of buildings is divided into four main stages: building construction (stage A), maintenance and operation (stage B), end of life and disposal (stage C) and next product (stage D) [31,32]. The focus of this research is construction materials with particular attention paid to strategies that diminish the related energy consumed and carbon emissions produced. Therefore, the operational water and energy (which evaluate the energy required to operate the building during its entire service life) were excluded. Further, the end of life stage (C + D) were grouped in this analysis because of the limited number of applications to the next product stage.

2.2. Cohen’s kappa

Two authors filtered the shortlisted articles. To do so, each author independently scanned the titles and abstracts of the articles that were downloaded from the databases. Based on this, each author decided whether an article should be included or excluded and stated the reasons for exclusion (examples of reasons can be found in Section 2, step 3). Cohen’s kappa was then adopted to calculate the level of agreement between the two authors, as suggested by Gwet [33]. The resulting
Cohen’s kappa is 0.86, representing a high agreement between the authors (see Appendix C; Cohen [34]).

2.3. Embodied energy, embodied carbon, and functional units

The terms environmental impact, environmental footprint, and impact were used interchangeably. These terms expressed the effect that construction materials and buildings have on the environment in terms of embodied energy and embodied carbon.

Embodied energy is defined as the sum of primary renewable and non-renewable energy that was employed to extract raw material sources, transport, and process them to then produce and dispose of the selected construction materials [35]. Hence, the overall embodied energy of a building is the amount of energy that is derived from renewable and non-renewable resources to produce building materials and components and is used to produce the building [36]. Similarly, the embodied carbon related to the same processes (often referred to as global warming potential) is the amount of the emissions that are produced in creating the construction materials and components as well as to construct the buildings [37,38]. Among more than 20 environmental impact indicators, those that analyze the embodied energy and carbon were chosen because they are the most commonly used in the literature of construction materials and buildings.

Two functional units were adopted for two different purposes. First, for evaluating the environmental impact of construction materials, the most common functional unit related to materials was used: the mass measured in kg (as will be discussed later in Section 4.1, the functional unit of some of the construction materials is modified). Therefore, the results belonging to this category are measured in MJ/kg (embodied energy) and in kg CO₂ eq/kg (embodied carbon). When data were provided in volume, it was converted into mass using values of density equal to 2,400 kg/m³ for concrete [39], 400–600 kg/m³ for timber (depending on the specific timber) and 8,000 kg/m³ for steel [40]. Second, the functional unit adopted to compare the impact of entire buildings is the measure of useable floor area: m² [41,42]. Some of the shortlisted studies calculated the buildings’ environmental impact using the entire building as the functional unit and expressed in total floor area [43,44]. When that was the case, the results were normalized by dividing their findings by this amount. Therefore, the functional unit employed in the second part of the meta-analysis is 1 m², and the results are presented as GJ/m² (embodied energy) and in t CO₂ eq/m² (embodied carbon).

3. Calculation

Fig. 2 presents the theoretical framework adopted in this research. The link between the environmental impact, the LCA methodological decisions and the LCA results of the materials studied in the literature is presented.

The framework results in a set of procedural guidelines, suggestions for practitioners and its associated environmental implications. Results from the SLR informed the LCAs’ methodological level of the final propositions and environmental implications. For example, it was observed that a lack of transparency in the definition of the adopted functional unit as well as other methodological choices make several LCA results impossible to replicate, which leads to the results being

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Fig. 2. Theoretical framework of buildings’ environmental impact. (EPS = expanded polystyrene.)

a Evidence collected from the systematic literature review

b Evidence collected from the meta-analysis.
perceived as unreliable or not trustworthy. Meanwhile, the results from the meta-analysis were employed to inform the proposed procedural guideline. Specifically, statistical analyses of the collected 677 LCA results were adopted to produce the benchmark proposed in the guideline described in Section 4.2.

3.1. Embodied energy and carbon of construction materials

From the analysis of the shortlisted papers, 8 main construction materials emerged: concrete, reinforcement bars, steel, timber, bricks, tiles, insulation, and plaster (Fig. 3 and Fig. 4). Except for concrete, the data extracted from the literature are distributed over a wide range of tiles, insulation, and plaster (Fig. 3 and Fig. 4). Except for concrete, the meta-analysis shows that concrete is also related to the smallest impact per kg: the median of embodied energy and carbon is equal to 1.11 MJ/kg and 0.19 kg CO₂ eq/kg, respectively. Further, meta-analysis results illustrate that concrete is the material that results in the smallest variability of outcomes: its interquartile range varies between 1 and 1.3 MJ/kg, and 0.14 and 0.28 kg CO₂ eq/kg. By comparison, the interquartile range of structural steel varies between 21.9 and 35.3 MJ/kg, and 1.7 and 2.8 kg CO₂ eq/kg. The reason for the results of impact assessments of concrete converging to a central value might be either because concrete is widely known and studied [45], or because its manufacturing processes involve fairly simple steps, machinery and established chemical reactions [46]. Such a narrow interquartile range implies that LCA practitioners and scholars can use the median values provided here with confidence in their applications.

3.1.1. Environmental impact of concrete

According to this SLR, concrete is the most studied material. The meta-analysis shows that concrete is also related to the smallest impact per kg: the median of embodied energy and carbon is equal to 1.11 MJ/kg and 0.19 kg CO₂ eq/kg, respectively. Further, meta-analysis results illustrate that concrete is the material that results in the smallest variability of outcomes: its interquartile range varies between 1 and 1.3 MJ/kg, and 0.14 and 0.28 kg CO₂ eq/kg. By comparison, the interquartile range of structural steel varies between 21.9 and 35.3 MJ/kg, and 1.7 and 2.8 kg CO₂ eq/kg. The reason for the results of impact assessments of concrete converging to a central value might be either because concrete is widely known and studied [45], or because its manufacturing processes involve fairly simple steps, machinery and established chemical reactions [46]. Such a narrow interquartile range implies that LCA practitioners and scholars can use the median values provided here with confidence in their applications.

3.1.2. Environmental impact of steel

Steel, both as structural steel and reinforcement bars, is the second most impacting material (after expanded polystyrene). Steel embodies 28.3 MJ/kg and 2.2 kg CO₂ eq/kg as structural steel, and 17.9 MJ/kg and 1.6 kg CO₂ eq/kg as reinforcement bars (median values). Although steel is one of the most popular construction materials, it was found that its embodied energy and carbon vary substantially, ranging from 6.36 to 85.5 MJ/kg (which has been considered an outlier value in the representation), and from 0.34 to 4.55 kg CO₂ eq/kg. The variability of these results might be related to the geography of the study, as the highest environmental impact of structural steel was registered in Australian and European studies (e.g., Crawford [47], Fay et al. [48], Monahan and Powell [38]): Australia usually imports virgin steel from China, which increases the impact of such materials due to transport (material transport is included in the production stage, A.4; see EebGuide [49], Qiangeng et al. [50], Yellishetty and Mudd [51]). As discussed below in Sections 3.3 and 4.2.2, the adverse environmental impact of transport could be decreased by sourcing and refining local materials or changing means of transport (see Section 4.2.2, Strategy 5 for more information).

3.1.3. Environmental impact of timber

Timber is widely considered as one of the most environmentally friendly materials because its structure captures carbon from the atmosphere as CO₂ [52]. It might then appear counterintuitive that producing one kg of timber for buildings embodies high amounts of energy (7.5 MJ/kg, median), whilst its embodied carbon per kg remains comparable to the embodied carbon for concrete (0.45 kg CO₂ eq/kg, median). These results might be due to three main factors. First, although trees capture carbon from their environment, the industrial processes involved in harvesting, drying, sawing, and transporting timber are energy intensive [53,54]. The gap between the embodied energy of timber structures and their embodied carbon has been assessed and can be explained by timber absorbing CO₂ from the atmosphere, contributing to a low amount of embodied energy. Second, the reason why timber has seemingly greater impact than concrete might be affected by the chosen functional unit (kg); such aspect will investigate this aspect in Section 4.1. Another reason for why the embodied energy and carbon of timber are greater than those of concrete is that the analyzed studies do not consider the end of life of timber, which is typically a stage when timber positively impacts on the environment. Further, timber from demolished structures is often biodegradable, which limits its environmental impact as it does not contribute to creation of landfill. This aspect will be considered in some detail in Section 3.2, which is concerned with evaluating the entire life cycle of timber structures (including end of life and next product stages, C+D). However, a sub-category of engineered timber products (such as cross laminated timber (CLT) or plywood) release their biogenic carbon in the atmosphere when decomposing, increasing CO₂ levels [55]. For this reason, buildings’ designers should focus on extending the life of these components or making them disassemblable and reusable [56].

3.1.4. Environmental impact of expanded polystyrene

In terms of embodied energy, the construction material with most impact by kg is expanded polystyrene (a common insulation material). Polystyrene embodies 95.7 MJ/kg and 3.2 kg CO₂ eq/kg (median values). Of the here embodied energy, the greatest amount (between 70% and 90%) is embodied during the acquisition of its primary raw material: hydrocarbon fuels [57-59].

3.1.5. Environmental impact of bricks, tiles, and plaster

Bricks, tiles, and plaster impact 2.8 MJ/kg and 0.24 kg CO₂ eq/kg, 5.5 MJ/kg and 0.76 kg CO₂ eq/kg, 3.6 MJ/kg and 0.23 kg CO₂ eq/kg, respectively (median values). Both clay and gypsum are natural materials, and their impact is mainly due to the heat required in their production processes: baking in ovens (bricks and tiles), and calcination (gypsum) [60]. Therefore, the production process of these materials in the building sector increases the impact of (a) total embodied energy by up to 18%, and (b) embodied carbon by up to 19%.

3.1.6. Correlation between embodied energy and carbon of construction materials

Through the meta-analysis it was possible to extract embodied energy and carbon to produce the studied construction materials. Further, to not lose information on individual data points, this information was linked to the countries where these materials were produced. Doing so allowed to explore correlations between the collected variables. Fig. 5 shows that there is a linear correlation between embodied energy and carbon. Perhaps unsurprisingly, a more thorough analysis of the data reveals data clusters of the single materials.

Fig. 5 shows a positive linear relationship between bricks and plaster embodied energy and emissions (and in both cases the coefficient of determination R² is close to 1). This means that the energy required to produce these two materials is associated with the resulting carbon emissions stemming from the production processes. The values that have been recorded for structural steel are also distributed along the regression line, with the exception of one outlier study (which was excluded from the calculation of the R² in the chart; Galan-Marin et al. [61]). Similarly, results on embodied energy and carbon of timber are distributed along a regression line, again, however, with the exception of one outlier (Moyano et al. [62]).

Fig. 6 shows that results for concrete are distributed mainly below and above both means of the two datasets, which demonstrates a positive correlation between embodied energy and carbon related to concrete production. Overall, these findings suggest that concrete follows the same pattern identified for structural steel, plaster, and brick. Further, the data show that, among the studied countries, Spain and Italy consume more energy and produce more carbon emissions to
produce expanded polystyrene, bricks and structural steel than the rest of the examined countries. Finally, from these data it was not possible to identify any pattern related to environmental effects of reinforcement bars and tiles, whose impact appears distributed randomly (Figs. 5 and 6). This SLR shows that most of the studies of the LCA of buildings investigate the environmental impact of concrete, timber, and steel structures. Such thematic analysis allowed to divide the sources depending on which of these three structural materials were studied.

3.1.7. Environmental impact of structures

Of the collected studies, 66 focused on building structures without additional components, such as finishing materials, insulation, doors,
windows, roof, and cladding. Excluding these additional components was helpful to gain a better understanding of the differences between concrete, timber, and steel of bare structures. Problematically, however, these studies mainly analyze the production stages of buildings, and do not provide enough results on embodied energy and carbon of maintenance and end of life LCA stages, therefore it is impossible to infer related conclusions. Consequently, the following sub-sections focus only on the environmental impact of the production stage of concrete, timber, and steel structures.

3.1.7.1. Embodied energy of structures. As shown in Table 1, concrete structures range in their environmental impact from a minimum of 0.3 GJ/m² to a maximum of 8.4 GJ/m² (e.g., Moyano et al. [62], Wu et al. [63]), but most results range narrowly between 1.1 and 4.6 GJ/m². Conversely, most timber structures embody between 2.3 and 5.5 GJ/m² (e.g., Li and Altan [64], Pierobon et al. [65]), which means that, in the main, timber structures embody more energy than their concrete counterparts. Similarly, steel structures embody between 1.4 and 6.5 GJ/m² (e.g., Li and Altan [64], Su and Zhang [66]). These results suggest that, in terms of embodied energy, concrete structures are preferable over timber and steel structures. That said, the difference between energy produced from fossil fuels and energy from renewable resources could not be measured as usually it was not mentioned in the retrieved sources. If the energy used to construct these structures were partially renewable, the direct impact of these values on the environment could be reduced.

3.1.7.2. Embodied carbon of structures. Table 2 summarizes the results
of the embodied carbon of concrete, timber and steel structures. As shown here, steel embodies slightly less carbon than concrete although the difference in embodied carbon between concrete and steel structures is negligible. When it comes to embodied carbon, timber emerges as the more environmentally friendly material because it stores carbon in the structure and thereby removes it from the atmosphere. Specifically, embodied carbon of timber structures ranges between 445.6 and 333.5 kg CO$_2$ eq/m$^2$ (e.g., Mackova et al. [67], Pierobon et al. [65]), and a median equal to 95.7 kg CO$_2$ eq/m$^2$.

### 3.1.8. Differences across construction materials and life cycle stages

Several articles were gathered that quantified the LCA of the entire building including non-structural materials so as to analyze the impact from production to demolition. Results of these articles were divided into the three main life cycle stages: building (stage A), maintenance (stage B) and demolition (stages C + D). This was not always possible because some studies evaluated only the production stage (e.g., Cornaro et al. [68], Takano et al. [69]) while others focused only on the production and end of life stages (e.g., Guo et al. [70], Liu et al. [71]).

The SLR produced 130 LCAs of entire buildings, which include the structure and the finishing materials. Some of these studies include both maintenance and end of life stages in their assessment. Both embodied energy and carbon increase throughout the life cycle because more materials are produced and consumed to maintain and refurbish the buildings during their use. However, recycling of concrete leads to saving of up to ~0.8 GJ/m$^2$ once the structure is demolished. Similarly, timber and steel enable savings in terms of embodied carbon (~0.1 t CO$_2$ eq/m$^2$; Fig. 7 and Fig. 8).

Across the entire life cycle, buildings with a timber structure embody...
significantly less energy and carbon. Thus, in exploring median values, the impact of timber structures is 57% less than that of the concrete structures in terms of embodied energy and 32% less in terms of embodied carbon. In contrast, steel buildings save only 9% in terms of embodied energy, and 15% in terms of embodied carbon compared to concrete structures (Fig. 9).

3.2. Transport

The transport of construction materials and components can significantly increase the embodied energy and carbon of buildings [29]. Being dependent on the geographical location of the building and industry-to-site distances, the impact of transport on construction materials varies substantially. For example, moving materials from their production facilities to the construction site could impact from 0.1% to 4% of the total building (results comparable in terms of embodied energy and carbon; see Chang et al. [72], Li et al. [73], Scheuer et al. [74], and Nässén et al. [75]). This meta-analysis measured the impact of the three main means of transport, truck/road, train/railway and marine shipment. Materials transport has often been the subject of uncertainty analysis due to its variable nature [76,77], and finding its related embodied energy and carbon could be challenging [73]. In addressing this issue, the collected values are proposed in Table 3, measured in impact per mass of transport material (in tons) and shipping distance (in km), their median and mean values and the related useful sources.

4. Results and discussion

4.1. Making sense of the impact of structural materials – from mass to specific strength

A limited number of cases employed the volume (in m$^3$) of concrete as a functional unit to measure its environmental footprint (for example, Gan et al. [87], Teh et al. [88]). More often, the chosen functional unit was the mass of materials, expressed in kg. Therefore, Section 3.3 is a summary of the literature on the energy and carbon embodied to produce 1 kg of concrete, timber, and steel. It should be recognized, though that this might be misleading. The design of a typical structural element (a beam, or a column) must primarily take into account its load-bearing capacity, its structural strength and its strength at failure point. In normal circumstances, the mass must be optimized only to reduce any additional load. In other words, the mass of a structural element – or of a structural material – says little about its function as a structural
Renewable and Sustainable Energy Reviews 143 (2021) 110935

Table 3

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component.

To address this issue, the functional unit of concrete, timber and steel was shifted from mass to specific strength.¹ Specific strength can be defined as the force per unit area at failure (measured in kN/m²), divided by the density of the material (measured in kg/m³). This new functional unit is measured in (kN m)/kg, and, in considering the strength of the materials, better suits the purpose of analyzing the impact of structural materials.

Shifting the functional units can be done by dividing the previously calculated embodied energy and carbon of concrete, timber, and steel by their specific strength. This means that the new functional units of embodied energy and carbon are MJ/(kN m) and kg CO₂ eq/(kN m), respectively (the results are summarized in Table 4).

The new functional unit helps in understanding the impact of structural materials. Specifically, in terms of embodied energy, timber impacts about 54% compared to concrete and 10% compared to steel in terms of embodied energy, and only 17% of concrete and 7% of steel in terms of embodied carbon. In combination with the fact that typically steel structures are built with the support of substantial amounts of concrete, these results confirm (cf. Section 3.4.1) that timber structures help decrease buildings’ environmental impact, especially in terms of embodied carbon.

4.2. Revisited life cycle assessment method – a procedural guideline

The main objective of this paper is to create a comprehensive procedural guideline that benefits practitioners. Specifically, two key steps are added to the commonly found LCA procedural guidelines. To distinguish from the pre-existing four steps of LCAs (i.e., Goal and scope definition, Life cycle inventory, Life cycle impact assessment and Results interpretation), the two added steps are numbered with roman numerals: I. Result ranking, and II. Project improvement (Fig. 10). The first added step helps LCA practitioners to classify their results in a ranking chart (provided that the structural material is concrete, timber or steel).

¹ To be precise, the functional unit shifts from mass to specific strength per unit of mass, or from kg to kN m. For the sake of simplicity, this unit was referred as specific strength.

The second added step can assist practitioners in decreasing the embodied energy and carbon of buildings. As such, the second step consists of strategies that can be applied to diminish the environmental impact of the used materials. As a corollary, the ranking chart below (Fig. 12) helps practitioners to identify whether their case studies are outliers because their impact is lower than a provided limit, or excessive, suggesting that the LCA needs to be improved (or that practitioners may have made a mistake in their LCA).

4.2.1. Step I. Result ranking

The result ranking step follows the life cycle impact assessment step, in which the results of the application of the LCA to the studied building are obtained first. The value obtained could fall into one of the six possible sections of Fig. 11. To rank the results obtained through the previous LCA steps, the values in Fig. 12 can be used. These values were calculated in considering the sum of the results obtained for all the four life cycle stages considered.

In summary:

a) Results that fall into this category are top outliers. These represent buildings that embody an excessive amount of energy and carbon, which could be due to factors such as the amount of non-recyclable materials used, non-optimized material use and long-distance transport. These buildings can be improved by following the suggestions proposed in the next LCA step (Step II. Project improvement). A check of the calculation is recommended.

b) Results that fall into this category belong to the 25% of the most impacting buildings analyzed. Practitioners should consider applying the strategies proposed in the next LCA step (project improvement) to decrease their environmental impact.

c & d) These sections include the interquartile range of results, or the 50% of the results that are closer to the median value. A building whose impacts are within these groups are considered average, however, improvements are strongly recommended.

e) Buildings whose results fall into this section are considered the lowest impacting cases. The practitioners could decide to test the outcome of applying strategies proposed in the project improvement step to decrease the impact of the studied building.

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4.2.2. Step II. Project improvement

The project improvement stage guides practitioners on applying one or more of the following strategies that have been revealed in the shortlisted articles.

Table 5 summarizes the strategies, the percentage of the impact that could be saved by adopting them, and selected references. These percentages represent the possible savings of embodied energy and carbon over the whole buildings.

4.2.3. Strategy 1. material substitution

4.2.3.1. Timber in place of concrete. The most applied strategy to diminish buildings’ impact is material substitution [96,106,107]. More specifically, to decrease buildings’ impact, timber is more effective than both concrete and steel. Depending on the dimensions of the building, cross laminated timber has been used in high-rise structures (up to 53 m, 18 floors; see Pei et al. [108]) because of its high structural resistance [106]. Engineered timber can be employed in low-to mid-rise structures (up to 30 m, 6 floors; see Tollefson [110]). A less popular, yet promising type of material is agricultural waste products, which could substitute
concrete and other traditional materials, and in doing so, diminish the carbon emissions by storing carbon in its structure [68,111]. Using timber instead of concrete, whenever feasible, allows a decrease in buildings’ environmental impact up to 43% in terms of embodied energy and 68% in terms of embodied carbon.

4.2.3.2. Steel in place of concrete. Although it has been shown to have limited effectiveness in reducing the environmental impact of concrete, substituting concrete with steel remains a popular practice (e.g., Azzouz et al. [96] and Tavares et al. [97]). However, particularly in high-rise buildings, steel structures require a considerable amount of concrete for their foundations and supporting components (such as load-bearing staircases) [64,69]. Although the impact of steel and concrete is similar in terms of embodied energy and carbon, steel structures have several advantages over concrete. For example, they are usually lighter, requiring less material and in turn decreasing material depletion [96]. Steel components are manufactured in controlled factories, with lean production systems that help save waste [112], and can be employed in modular buildings, which are quicker to build than concrete or timber buildings [102]. Further, steel is preferred when it comes to material separation and recycling, as it can be easily segregated from other materials [113]. However, a steel structure still requires a considerable amount of concrete, therefore strategy helps reduce the environmental impact of buildings only up to 9% in terms of embodied energy and 15% in terms of embodied carbon.

4.2.4. Strategy 2. recycle

4.2.4.1. Recycled concrete. Recycling is often associated with the circular economy concept, the practice of turning waste into new resources [114], and recycling of construction and demolition waste is often linked to a saving of greenhouse gases [115]. Although recycling implies substantial amounts of materials saved from landfill, this practice often under-delivers. Concrete, for example, is not fully recyclable, as, after the recycling process, its next product—typically aggregates such as gravel—has inferior structural qualities [116]. Further, concrete made from recycled components often requires virgin components, such as cement. Down-cycling is the preferred term to describe this process [117]. Down-cycling in the context of concrete buildings refers to a process whereby concrete is crushed into gravel—a product that has inferior qualities than concrete. Additionally, recycling concrete leads to embodied energy and carbon savings in only a limited number of cases [98]. Overall, recycling concrete allows a range of saving between –5% and 29% in terms of embodied energy and between 6% and 18% in terms of embodied carbon.

### Table 4

Embodied energy and carbon of concrete, timber (radiata pine) and structural steel with the varied functional unit.

<table>
<thead>
<tr>
<th></th>
<th>Strength at failure (MN/m²)</th>
<th>Density (kg/m³)</th>
<th>Specific strength (kN m/kg)</th>
<th>Embodied energy (MJ/kg)</th>
<th>Embodied carbon (kg CO₂ eq/kg)</th>
<th>Embodied energy (kJ/(kN m))</th>
<th>Embodied carbon (CO₂ eq/(kN m))</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete – M35</td>
<td>35.0</td>
<td>2400.0</td>
<td>14.6</td>
<td>1.1</td>
<td>0.19</td>
<td>75.4</td>
<td>13.71</td>
<td>Bischoff and Perry [89]</td>
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<td></td>
<td></td>
<td></td>
<td>Vecchio and Collins [90]</td>
</tr>
<tr>
<td>Timber – pine</td>
<td>78.0</td>
<td>400.0</td>
<td>195.0</td>
<td>8.0</td>
<td>0.45</td>
<td>41.0</td>
<td>2.30</td>
<td>Tsoumis [91]</td>
</tr>
<tr>
<td>Structural steel</td>
<td>505.0</td>
<td>8000.0</td>
<td>64.7</td>
<td>25.5</td>
<td>2.20</td>
<td>404.0</td>
<td>34.85</td>
<td>Ames et al. [93]</td>
</tr>
</tbody>
</table>

a Median values of embodied energy and carbon discussed in Section 3.3.

b Embodied energy and carbon expressed in the new unit prefix (from MJ to kJ and from k CO₂ eq to CO₂ eq) to improve readability of these smaller values.

**Fig. 10.** LCA revisited with the addition of the two new stages: stage I, Results ranking, and stage II, Project improvement.
4.2.4.2. Recycled timber. Timber too can be down-cycled, but often paints, glues and other chemicals used to protect the components during the building operation make this process unpractical. End of life strategies of timber components include reprocessing it as a fibrous material, incineration or conversion to a gaseous or liquid fuel [118]. In terms of embodied energy, these practices allow a saving between 7% and 22% in terms of embodied energy, and between 15% and 200% in terms of embodied carbon. In considering turning timber into a fuel, this last extreme amount is obtained in calculating the CO$_2$ that would have been emitted to produce the same heat with similar non-renewable fuel.

4.2.4.3. Recycled steel. Recycled steel produces a material with structural characteristics similar to virgin steel. To date, steel recycling is considered (one of) the best end of life strategies for construction materials [74,96]. This is because of both its considerable savings in terms of embodied energy (between 40% and 45%) and embodied carbon (up to 60%), and because nearly 100% of steel scrap can be reintegrated into new steel [87].

4.2.5. Strategy 3. by-product integration

The environmental impact of concrete is largely due to the impact of cement, one of its main ingredients [119]. For this reason, integration of industrial waste as by-products into concrete could be a successful strategy to decrease the cement-ratio in concrete, and at the same time manage waste from other industries [88]. Slag, in different forms such as ground granulated slag from blast-furnace is being used in concrete structures in place of up to 75% of cement. This helps to diminish the overall embodied carbon of concrete production by up to 66% [87,120]. Bayer liquor, which results from the production of alumina, can be used to substitute cement into concrete, and it helps decrease the embodied energy of up to 33% of concrete made with Portland cement [27]. Similarly, up to 35% of fly ash could successfully be used instead of cement in the concrete production process, without significantly

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Fig. 11. Six different scenarios of building impact ranking.

Fig. 12. Box whiskers plot of embodied energy (left) and embodied carbon (right) of the building results collected in three construction materials: concrete, timber and steel.
Table 5
Strategies to decrease the buildings’ embodied energy and carbon, and their percentual savings.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Saving of EE (%)</th>
<th>Saving of EC (%)</th>
<th>Notes</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Material substitution</td>
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</tbody>
</table>
| Timber in place of concrete                   | 43                | 68                | Results calculated for a mix of CLT and timber studs, joints, and trusses. Timber structures usually involve a substantial amount of concrete. End of life and next product stages are not included. | Ajayi et al. [64]  
Á vajlenka et al. [95]  
Azrou et al. [96]  
Cornaro et al. [68]  
Guo et al. [70]  
Svajlenka and Kozlovska [84]  
Takano et al. [69]  
Tavares et al. [97] |
| Steel in place of concrete                    | 9                 | 15                | Steel structures usually involve a substantial amount of concrete. End of life and next product stages are not included. |                                              |
| 2. Recycle of concrete                        |                   |                   |       |                                              |
| Concrete                                      | −5 ± 29           | 6 ± 18            | Recycling concrete is related to a negative saving, meaning that this operation has an adverse environmental impact. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates. | Blengini [9]  
Chang et al. [78]  
Chau et al. [98]  
Gan et al. [87]  
Gao et al. [99]  
Li and Altan [64]  
Liu et al. [71]  
Yan et al. [29]  
Thormark [100] |
| Timber                                        | 7 ± 22            | 15 ± 200          | Recyclability of timber products varies substantially between countries and regulations. Some studies considered energy and carbon recovery using timber as fuel as a recycling strategy. |                                              |
| Steel                                         | 40 ± 45           | 22 ± 60           | Up to 80% of steel is typically recycled into new material, which maintain the structural characteristics of virgin steel. |                                              |
| 3. By-product integration                     | 16 ± 33           | 21 ± 63           | Results related to the substitution of different amounts of by-products (i.e., Bayer liquor, fly ash, volcanic ash, ground granulated blast-furnace slag) instead of cement into concrete. Cement’s EC is 248 higher than graphene nanoplatelets’ EC, which is a safe substitution in concrete. | Jamieson et al. [27]  
Gan et al. [87]  
Kupwade-Patil et al. [28]  
Papanikolaou et al. [101]  
Teh et al. [88] |
| 4. Design for disassembly and reuse           | 81                | 18 ± 88           | Although the literature suggests that concrete structures can be reused multiple times, local regulations and guidelines. | Aye et al. [102]  
Cruz Rios et al. [103]  
Dara et al. [104] |

Table 5 (continued)

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<tr>
<th>Strategy</th>
<th>Saving of EE (%)</th>
<th>Saving of EC (%)</th>
<th>Notes</th>
<th>Sources</th>
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</table>
| 5. Change of means of transporta,b             | 92                | 20 ± 74           | The environmental impact of transport could undermine the savings due to recycling and reuse practices. Percentages calculated for the same number of km in comparing marine shipping with transportation by truck. | Eberhardt et al. [105]  
Minunno et al. [56]  
Cruz Rios et al. [103]  
Gan et al. [87]  
Paulsen and Sponto [62]  
Peng [85]  
Svajlenka and Kozlovska [84]  
Yang et al. [85]  
Yu et al. [86] |

a Recycling concrete yields a negative saving, meaning that this operation has an adverse environmental impact in terms of EC. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.

b The savings due to changes of means of transport are intended over the median impact of transports, not over the whole building.

affecting the structural characteristics of concrete. The concrete prepared with fly ash emulates up to 33% less energy than concrete mixed with only cement [57].

Interestingly, not only by-products are used as cement substitution. Researchers are experimenting innovative materials to substitute cement into concrete. One of these, Pozzolanic volcanic ash, could take the place of up to 50% of cement in concrete. Doing so decreases concrete’s embodied energy by up to 16% [28]. Another novel material, graphene nanoplatelets could be used to substitute up to 5% of cement in reinforced concrete, resulting in a 21% reduction of concrete’s embodied carbon [101].

4.2.6. Strategy 4. design for disassembly and reuse

Design for disassembly and reuse of building components has the potential to significantly decrease the environmental impact of buildings, since reused components require little modification from their original shape and structure [30,113,121]. Therefore, once disassembled and adapted, these components could be reintegrated into the market for construction materials [103,122]. This strategy could be applied to both panels and volumetric prefabricated structures, such as modular buildings. Alas, this meta-analysis revealed that reuse of building components remains under-researched [123,124]. That said, in some cases, designing building components that can be reused in their second life was associated with a decrease of up to 81% in terms of embodied energy and 88% in terms of embodied carbon [56,102].

4.2.7. Strategy 5. change of means of transport

The impact of material transport varies depending on the geographical location of the building and the means of transport. The means of transport can increase the overall embodied energy and carbon from as little as 0.04%–8.4% in terms of embodied carbon and energy respectively [82,85]. Three main means of transport can be employed for construction materials: road/truck, railway, and marine shipping. Although marine shipping is, for some countries, the only available option for sourcing materials [125], in other cases it could also help decrease the impact of building for two main reasons. First, these results prove that marine shipping impacts only about 8% in terms of embodied energy and 26% in terms of embodied carbon, when compared to transport by truck [78,79]. Therefore, for every 100 km of transport by road, materials could be sourced from distances of up to 400 km by sea,
producing half of the impact in terms of embodied energy, and the same impact in terms of embodied carbon [74,86,126]. Second, sourcing from overseas often allows designers to choose from a greater variety of products than those which might be available locally [127,128]. This could help designers find and consider materials with a lower environmental footprint.

5. Suggestions to LCA practitioners and scholars

5.1. Comparison and improvements of the results of an LCA

LCAs can be complex procedures. Particularly, in stage 1 (i.e., goal and scope definition), they involve several variables such as defining functional unit [17]. Despite complexity, LCA practitioners are expected to conduct and interpret as well as improve upon its results. More problematically still, to date, there is little guidance on how to interpret LCA results in a building context. Consequently, LCA case studies are often ad hoc and piecemeal, leaving its practitioners and researchers confused about how to interpret LCA results, among other issues. To overcome this challenge, this paper developed a procedural guideline that helps practitioners to compare and improve embodied energy and carbon in a building context (provided that the structural material is concrete, timber, or steel). As shown in Section 4.2, the procedural guideline unfolds in two main steps. First, the proposed guideline includes a benchmark that allows LCA practitioners to compare their findings with previously published LCA results (the box-plot diagrams shown in Fig. 12 make this process quick and easy). Second, the proposed guideline assists practitioners in improving the LCA results so as to obtain substantial savings in terms of embodied energy and carbon. For example, this work helps practitioners to make informed decisions about what materials to use, the necessary degree of disassemblability of the building structure and so forth. Indeed, if LCAs are adopted in the early design stage of a building, these decisions have the potential to dramatically decrease the environmental footprint of buildings.

5.2. Considerations on functional units

Typically, substantial efforts are required throughout the LCA steps. Gathering accurate data, choosing the appropriate software, calculation method, impact databases, analyzing the results and consideration of possible improvements – LCAs can be overwhelming processes. Among these steps, the importance of selecting the most appropriate functional unit can be disregarded. As shown, however, functional units can significantly affect the results of an LCA. Studying the impact of producing 1 kg of a material is useful to compare the environmental impact of materials that perform the same function. However, doing so would yield little insight on the product whose function and use are substantially different. A solution to this challenge could be the adoption of a functional unit that considers the function of a building component, instead of its mass. If, for example, a column is designed to support a vertical load, its specific strength (or the force per unit area at failure) can be adopted. Doing so is beneficial because it takes into consideration the structural resistance of a material, which is a parameter strictly related to its load-bearing function, rather than the mass of the component materials of the column.

6. Conclusions and further research

Three main literature gaps are addressed in this paper. The first gap is the lack of a comprehensive benchmark of LCA results, the second gap concerns the lack of guidelines that allows LCA practitioners to compare and improve their results with previous LCAs. The third gap is created by the lack of guidance on selecting the proper functional unit for LCAs in a building context. To address these gaps, the review collects, summarizes and reports the results of a meta-analysis of 181 academic articles on LCA. From these articles, 677 results of LCAs are extracted, of which 370 are related to eight construction materials and 307 to buildings’ embodied energy and carbon. From the empirical evidence, a summary of the energy and carbon embodied in construction materials and buildings is provided. Following the observations on the environmental impact of construction materials and buildings, the combination of the SLR and meta-analysis of related studies allowed the production of a practical guideline that expands the traditional LCA method. This guideline is designed to assist LCA practitioners in comparing and diminishing the adverse environmental impact of their constructions. The guideline unfolds in two steps. The first step proposes a ranking system of buildings’ embodied energy and carbon. LCA practitioners can use this ranking system to compare the preliminary results of their LCAs with the results that have been comprehensively collected in this review. In so doing, practitioners can benchmark and therefore corroborate their results. The second step suggests several strategies to diminish the negative environmental impact of buildings. These strategies are designed to inform the LCA practitioners of how much saving in terms of embodied energy and carbon can be yielded by, for example, substituting concrete frame with steel, or adopting modularized and disassemblable building construction systems.

7. Further research

From the SLR and meta-analysis, three important research areas and associated questions emerged:

- Retrofitting to reduce running costs of buildings: What is the link between embodied energy, embodied carbon, and water consumption, and how do they affect buildings’ running costs? In addressing this question, scholars could then also review, propose, and test strategies to help reduce these running costs as well as explore nearly- or net-zero energy building concepts’ role in decreasing ongoing adverse environmental impacts of buildings.

- Smart building systems: What is the role of smart building systems, and how can such systems help creating a circular economy of buildings? Additionally, scholars could explore technological advancements associated with the circular economy of buildings, such as building information modelling and tracking devices, which is especially important when applied to disassemblable buildings [124, 129]. Similarly, artificial intelligence, smart buildings, modular building systems, sensors, and the adoption of predictive control methods might help building designers in keeping components in the material loop.

- Carbon capture technologies: How can carbon capture technologies be integrated into buildings? More specifically, scholars could investigate an industrially and environmentally viable pathway toward carbon capture implementation at grand scale. Such implementation strategy could play a key role in leading toward carbon neutral buildings. However, more research is needed to discover more efficient ways to capture and store CO₂ into construction materials.

Main contributions

This paper makes three main contributions to the body of knowledge concerned with LCAs in the building context. First, a conceptual contribution is made by defining and adding new procedural guidelines to the established LCA method. This simple two-step procedural guideline is designed to help LCA practitioners to rank and improve their LCA results. In the first step, LCA practitioners can compare their results with those obtained in the identified 307 LCAs. This step helps overcome several difficulties that are typically found when comparing LCA results (for an overview of these difficulties see Cabeza et al. [8], Eberhardt et al. [105], Hu [3] and Nwodo and Anumba [130]). The project improvement step (or step II) suggests five strategies that could be applied to a building to decrease its embodied energy and carbon. These
strategies are linked with their expected percentage of savings. This step reveals that, for example, substituting cement with by-product integration could yield savings of up to 33% in terms of embodied energy and up to 63% in terms of embodied carbon. Or, designing a building for disassembly and reuse allows a saving of up to 81% of embodied energy and 88% of embodied carbon. The guideline is designed to be integrated with any standard LCA method; specifically, the two steps follow the life cycle inventory analysis step, which is part of the standard LCA method.

The integration of the proposed guideline with the LCA method allows LCA practitioners to adopt it in juxtaposition with the standard iterative and recursive LCA method. Such a juxtaposition is beneficial to the practitioners because it allows them to integrate the suggested guideline into their LCAs using the same data that had been collected and maintaining the goal and scopes as they had already been defined.

The second contribution of this paper is empirical. Through a meta-analysis, it helps to compare and control the environmental impact of construction material and buildings. Further, in making sense of the embodied energy and carbon related to the construction sector, the paper informs scholars, practitioners and policy makers on the impact related to different materials. The findings could thus be beneficial to anyone seeking to make evidence-based choices on new or existing policies on construction materials production, building maintenance and end of life practices.

The third contribution is the identification and description of patterns and correlation between the 677 results of the LCAs that collected and analyzed. These results corroborate and validate the usefulness of applying LCAs in a building context thus supporting several previous findings and contentions (e.g., Bakhshi and Sharon [131], Rashid and Yusoff [32] and Sharma et al. [132]). More specifically, the narrow interquartile ranges and the presence of only a few outliers amongst the analyzed LCA results suggest that the data are homogeneously clustered around the median values examined. Such homogeneity confirms that LCA is a potentially invaluable tool to quantify buildings’ environmental footprint.

Although the paper has gone some way towards resolving underlying uncertainties related to LCA results and helping practitioners to predict the outcomes of their LCAs, more research is needed to decrease the impact that buildings have on the environment (in the construction phase and beyond). The commitment of future scholars and practitioners could be the decisive factor in the race for a greener and more sustainable built environment. Therefore, further research could examine the impact of operations and logistics of buildings, including additional environmental indicators and continue to push the boundaries of the reviewed LCA method.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to acknowledge funding from the Australian Research Council’s Center for Advanced Manufacturing of Prefabricated Housing (ARC CAMPH), grant number: IC150 1000 23.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.110935.

Author contribution

Roberto Minunno: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing – original draft; Writing – review & editing. Timothy O’Grady: Investigation Gregory M. Morrison: Writing – review & editing, Supervision Richard L. Gruner: Writing – review & editing, Supervision.

References


