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A critical review of life cycle assessment benchmarking methodologies for construction materials

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ABSTRACT

As it stands, the construction sector accounts for a significant proportion of global emissions. The majority of these emissions can be associated with material production. As a result, the importance of quantifying these environmental impacts is continually increasing. However, there is a current lack of guidance and methodologies regarding how to benchmark the impacts of construction products, and thus achieve more transparent environmental reporting and decision-making. Therefore, the aim of this study was to review engineering life-cycle assessment (LCA) literature and applicable standards to identify the key methodological variables required and the key steps for a sector-wide methodology. This was carried out via a bibliographic search for indexed, peer-reviewed journal publications and conference proceedings, project reports, and standards for constructed assets. From the search conducted, 23 documents and 4 standards were selected for review as relevant for this study. As a result, five key constituent methodological variables (study scope; model typology; benchmark approach; database selection; benchmark type) and three key steps (data collection; LCA; benchmark generation, with the option for Data Envelopment Analysis) were identified. Furthermore, considering the novel ISO 21678:2020, specific benchmark pathways were defined for the four types of benchmark values which can be obtained: limit, reference, short- and long-term. The definition of this set of steps, key methodological variables and the authors' recommendations for the construction sector constitute the first LCA benchmarking methodology on this field.

1. Introduction

The construction sector is currently showing many initiatives for more sustainable asset management, with its increased research into and use of more environmentally friendly technologies. For example, increasing the use of recycled materials, co- and by-products, and reduced energy-consumption technologies (e.g., reducing manufacturing temperatures) [9,39,43,50]. Construction products are an essential cornerstone for society and economies, and their manufacturing interacts with fresh water, the local ecosystem, neighbouring businesses, and natural resources [47]. In response to these detrimental impacts, interest in Life-Cycle Assessment (LCA) is increasing within the sector, to quantify current practice and reduce energy and materials consumption, and hazardous emissions, in order to reach current global sustainability targets (i.e. Paris Climate Agreement in ten years [70] and the sustainable development goals by mid-century [69]).

LCA is currently an established tool, its use for construction products has been in development for decades [27,66] and framework documents have been elaborated [15,28]. However, no current benchmarking frameworks exist for comparing results or creating targets. While LCAs can be carried out through the use of both commercial or open-access tools, local or general life-cycle inventories (LCIs), primary or secondary data, it is still difficult to understand where an LCA output is on the spectrum of current or best practice. Thus, there is a current need for the development of a framework for establishing benchmarks, to reinforce and defend the use of novel technologies from an environmental standpoint.

Benchmarking, according to the ISO 21678:2020, is defined as: "*process of collecting, analysing and relating performance data of comparable buildings or other types of construction works*" [36]. In the European Commission's action plan for financing sustainable growth (i.e. the EU taxonomy), measures were announced to enhance the environmental, social and corporate governance (ESG) transparency of benchmark methodologies, as was an initiative to put forward standards for the methodology of low-carbon benchmarks in the European Union [16].

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Furthermore, more recently, the ISO 21678:2020 [36] was published, which defines sources and types of information applicable for benchmark generation, and the principles and rules for their declaration and communication for buildings and civil engineering works.

Within the construction sector, the majority of LCA benchmarking literature for engineered assets was found to be for buildings and in general is increasing in popularity. For example, some initiatives include the Athena Report on whole-building LCA benchmarks [3], the European SuPerBuildings Project [26], the Australian Materials and Buildings Products Life Cycle Inventory Database [1], the French “Construisons Ensemble HQE Performance” [31], and One Click LCA [52]. In literature some large-scale projects were also found, where Simonen et al. [65] and Röck et al. [58] considered 1191 and over 650 buildings in their projects, respectively. Furthermore, considering rating systems, in Germany all new federal buildings must be rated via the BNB rating system [25] and the BREEAM system is also offering incentives for whole-building LCAs [6]; where both systems have been found to be undertaking benchmarking exercises too [6,64].

As it stands, within the construction sector, the use of product category rules (PCRs) to generate environmental product declarations (EPDs) have made practice more harmonised. For example, in the pavement sector, the US National Asphalt Pavement Association’s [48], Rangelov et al. [56], and the Sustainable Highway Construction Guidebook [47] EPDs have been deemed appropriate for benchmarking activities. However, while the use of EPDs does generate harmonised LCA results, there is a lack of discussion on the creation of the benchmarks from a systematic or methodological point of view and on the variables present. Additionally, not only a sector-wide initiative would be needed, but also the consideration of the new ISO 21678:2020 defining benchmark principles, requirements and guidelines. Similarly, EPDs do not consider data limitations currently present, which was seen as a limitation in the building sector [26].

Therefore, in response to the need for a clear and transparent benchmarking methodology in the construction sector, to ease environmental reporting and support the management of assets with a greater environmental perspective, this paper aims to outline an LCA benchmarking methodology for construction products by 1) carrying out a systematic literature review for constructed assets, 2) deriving both methodological variables and key steps for benchmarking through quantitative and qualitative analysis, and 3) combining the results with the reporting guidelines laid out by the ISO 21678:2020.

2. Methodology

This study carried out a literature review to identify key steps and methodological variables present in benchmarking studies, thus to identify the most suitable manner to carry out a sector-wide study based on a solid foundation provided by previous studies.

To systematically review all relevant and prominent literature for the aim of this study, an extensive computerised search was carried out to identify the most prominent literature. The internationally recognised bibliographic database Scopus was used to identify the scientific literature which formed the basis of this study (Fig. 1).

The search carried out in the Scopus database, for articles relevant to the current study, was carried out via the use of Boolean operators “AND” and “OR” with the terms LCA/life-cycle assessment and benchmark/benchmarking. The review carried out covered 1997 to July 2020 (23 years and 7 months), as no articles prior to 1997 were found in the database. From the literature review described, 605 studies were found. As a posterior step, only engineering studies were selected, given the objective of this study. This reduced the number of studies to be considered to 278.

As detailed in Fig. 1, the Scopus search results then underwent a screening review to ensure relevancy to the aim of the study. This involved a two-step process, where firstly any study titles, keywords and abstracts which were deemed not relevant to the current study were removed (i.e. due to the term benchmark being referred to as a concept, and a methodology not being presented), followed by the full reading of the publications to ensure a systematic benchmarking methodology could be extracted. As a result of the screening process, a final set of 19 scientific articles were used for the basis of this study.

To further increase the completeness of the study, project reports were also searched for using the Google Scholar database, with the same search criteria used in the Scopus database. Additionally, benchmarking standards were also searched for to understand their suitability to the aim of the present study.

The selected studies were then completely reviewed according to the aim of this study, looking to identify the methodological variables and key steps for LCA benchmarking. This involved reviewing the aim, methodology, results, and conclusions for all of the selected literature. The findings from the literature review were also compared with the reporting guidelines laid out by the ISO 21678:2020.

3. Results

From the results of the systematic literature review, it was possible to identify that 1) benchmarking studies have increased greatly over the past decade, 2) there are no standards for construction product benchmarking, only reporting, 3) there are five key methodological variables for a benchmarking study, and 4) there are three key steps for carrying

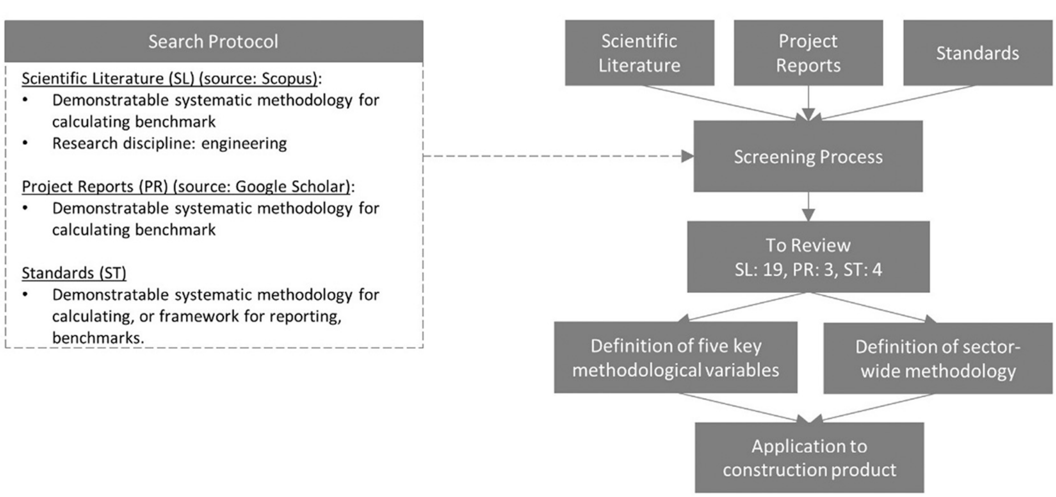

Fig. 1. Review methodology.

out a benchmarking exercise. Following on, the nature of previous benchmarking studies is explained, followed by the results from reviewing applicable standards, followed by the definition of the key methodological variables, and finally the definition of the three key study steps.

The publication of studies relevant to life-cycle assessment benchmarking has witnessed a steady increase from 2010 (Fig. 2), where 96.8% of the publications were made from 2010 to July [51] and from observing the first two quarters of [51] it could be inferred that this trend will continue. 2016 and 2019 are the years with the highest number of studies, with 72 and 92, respectively. From the literature search in the Scopus database, the majority of the studies found originated from the United States (21%), Germany (11%), Spain (10%) and Italy (10%), while the most prominent institutions in the field were found in Europe: ETH Zurich, Switzerland (18 studies), Danmarks Tekniske Universitet, Denmark (15 studies), Instituto IMDEA Energia, Spain (15 studies), Politecnico di Milano, Italy (14 studies), and Chalmers University of Technology, Sweden (13 studies). 20.3% of the studies are published in two peer-review journals: Journal of Cleaner Production (69 studies) and the International Journal of Life Cycle Assessment (54 studies).

3.1. Standards

From the search carried out, no standards were found to provide a systematic methodology for benchmarking life-cycle assessment results. A total of three standards were found to provide methodologies for the benchmarking of products. Meanwhile, only one recently released standard was found for benchmarking reporting; as briefly mentioned in Section 1. The scope and framework of these standards are summarised in Table 1.

The standards which provided a framework for product benchmarking were: EN 16231:2012, ISO 17258:2015, and the ISO 24523:2017. The EN 16231:2012 defines a five-step model for energy efficiency benchmarking, the ISO 17258:2015 covers the Six Sigma methodology for organisations, first laid out by Jack Welch for General Electric in 1995, and finally the ISO 24523:2017 provided voluntary guidelines for good benchmarking practice for drinking water and wastewater utilities.

Meanwhile, the ISO 21678:2020 provides the indicators, requirements, and guidelines for benchmarking reporting. In this standard, the sources and data types applicable for benchmark generation, and the principles and rules of benchmark generation and communication are defined.

From the assessment of the standards, specifically the EN 16231:2012, ISO 17258:2015 and ISO 24523:2017, it can be concluded that the general steps for benchmarking exercises are 1) setting an objective and plan, 2) measuring a characteristic of interest of a product, 3) analyse the data collected, 4) interpret the results and make decisions. Furthermore, the standards consider benchmarking as a circular and repetitive process. This is due to technologies and processes improving over time, and thus the reference values for practice must also be updated.

Table 1
Description of standards relevant to benchmarking.

Standard	Scope	Framework
Benchmarking reporting		
ISO 21678:2020 Sustainability in buildings and civil engineering works - Indicators and benchmarks - Principles, requirements and guidelines	Description of three types of values for benchmarks: limit, reference, and target values.	N.A. – Defines sources and types of information applicable for benchmark generation, and principles and rules for declaration and communication.
Product benchmarking		
ISO 24523:2017 Service activities relating to drinking water supply systems and wastewater systems - Guidelines for benchmarking of water utilities	Guidelines on good benchmarking practice of drinking water and wastewater utilities.	Benchmarking methodology model: 1) preparation & planning; 2) data acquisition; 3) determination of benchmarks; 4) analysis; 5) implementation.
ISO 17258:2015 Statistical Methods - Six Sigma - Basic Criteria Underlying Benchmarking for Six Sigma in Organisations	Methodology for establishing the level of quality, performance, and productivity of processes, products, and services according to Six Sigma principles	Encompasses the generation of benchmarks and the process of benchmarking according to Six Sigma principles: 1) define; 2) measure; 3) analyse; 4) improve; 5) control.
EN 16231: 2012 Energy efficiency benchmarking methodology	Guidance on the criteria to be used in order to choose the appropriate level of detail for the data collection, processing and reviewing which suits the objective of the benchmarking.	Benchmarking methodology model: 1) objectives and plan; 2) data collection and verification; 3) analysis and results; 4) presentation of results; 5) follow up (optional).

3.2. Identifying key methodological variables

The evaluation of the selected papers permitted the identification of five key methodological variables for benchmarking studies, and can be summarised as follows:

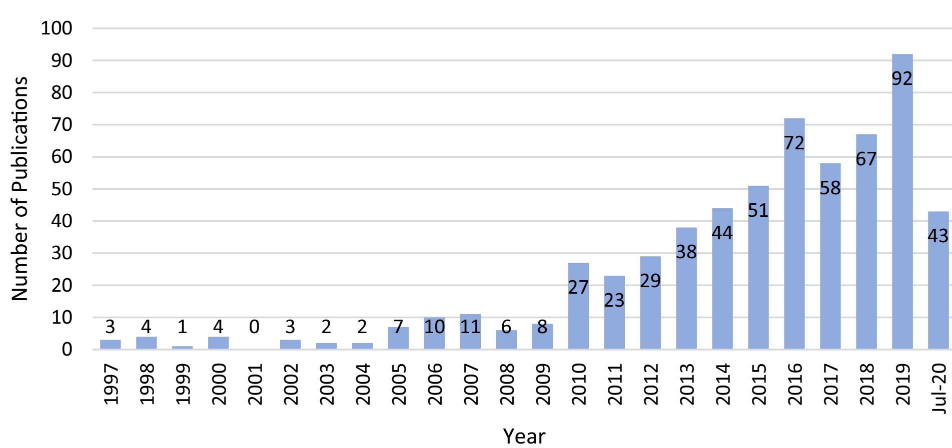

Fig. 2. Total number of studies on LCA benchmarking per year.

1) Study scope: the size of the study adopted. This was quantified via number of case studies considered, where either local process-based projects were undertaken considering only one case study, or a large-scale study undertaken considering multiple case studies;
2) Model typology: type of sample taken for analysis, can be external, internal, or hybrid. External are based upon a reference sample of a constructed asset (i.e. case studies), internal are based upon an asset modelled in accordance with construction standards (i.e. typically pre-construction) [22], and hybrid are a combination of both;
3) Benchmark approach: type of approach taken to define the benchmark, can be top-down or bottom-up [26,29]. Top-down refers to emission inventory data being defined from targets set from policies (e.g. setting benchmarks to achieve Paris Climate Agreement [70]) or industry-wide statistics, while bottom-up are derived from existing practice or theoretical models of current assets (i.e. modelling the constituent processes defined from the model typology) [3,32];
4) Database selection: source of data for generating benchmarks. This is important for creating a data quality or validity benchmark, and principally takes the form of commercial/open-source databases, collection of primary data, or literature review;
5) Type of benchmarks: values provided to end users. Different studies adopt different output values, where the majority provided a single value, but this can be seen to extended up to 5. According to the ISO 21678:2020, there are three key benchmark value types: limit (maximum undesired value), reference (current practice value), and target (ideal practice value).

From identifying these five key variables, it was then possible to quantitatively determine the most popular approaches according to the selected studies. In summary, it can be seen that a large-scale study (various case studies in different regions – Fig. 3A) based on built models (i.e., external) is most commonly adopted (Fig. 3B). The LCA is most commonly undertaken via a bottom-up approach (similar to a *process-based* LCA – Fig. 3C, where N.A. refers to studies where this was not determinable) and uses third-party data (Fig. 3D). Some large-scale studies were also able to create their own project specific

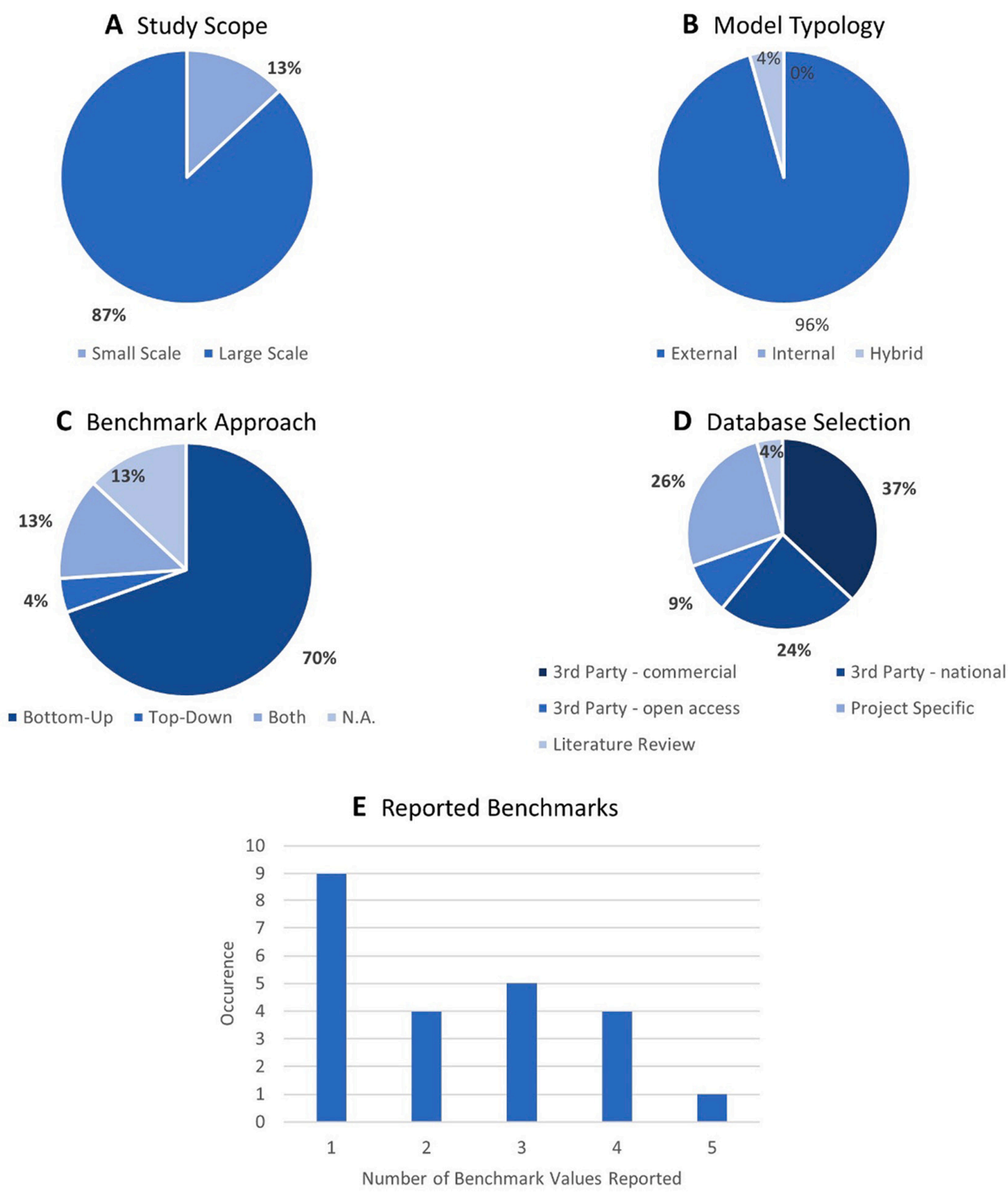

Fig. 3. Quantitative summary of literature review.

environmental impact database. Finally, 39% of studies reported only one benchmark, whereas only 22% reported three (i.e., the base number recommended by the ISO 21678 – Fig. 3E). This value could also be extended to four values, by utilising two target values (both short- and long-term target values).

The following sections will summarise the variables found in more detail and discuss the selected studies to identify the most optimal path for a sector-wide benchmarking study (on top of the quantitative results already discussed). A complete breakdown of the studies can be found in Appendix A.

3.2.1. Study scope

The local process-based studies reviewed were mainly found to provide "pilot" benchmark environmental impacts. For example, in the pavement sector, Saboori et al. [62] created benchmark figures for end-of-life pavement processes in the state of California, and Butt et al. [7] carried out a standalone benchmark study to quantify the environmental impacts from the life cycle stages (materials stage and construction stage) of the different layers of the erosion and shoulder of airfield pavements. While these would provide valid benchmark values, they would only be applicable to the region studied, because of the use of one specific case study and a region-specific LCI.

On the other hand, the majority of the studies found provided benchmarks considering various case studies and so were considered to provide "large-scale" benchmarks. These studies belonged primarily to the building sector and considered multiple case studies. For example, Simonen et al. [65] carried out a benchmarking study for buildings at a European level with 1191 case studies, while Röck et al. [58] did so with over 650. Furthermore, some studies assessed benchmarks from the building stock databases obtained from building sustainability rating systems. For example, Schlegl et al. [64] assessed 22 buildings from the DGNB rating system [12] and Hollberg, Vogel & Habert [30] carried out a benchmarking exercise for standard building components in Switzerland.

3.2.2. Model typology

The majority of studies were found to have an external typology, obtaining the benchmarks from case-study evaluation (i.e., post-construction). For example, as seen for various building studies, benchmarks were obtained from case studies considering from 5 to over 1000 homes [40,54,64,65]. Some rating systems also use external benchmarks, such as DGNB [12] and BREEAM [5,53].

Meanwhile, none of the studies assessed purely used internal benchmarks (i.e. internally-generated model typically according to construction standards and pre-construction) [22,45]. However, this type of benchmarking can be seen in the LEED [71] and BE^{2}ST-in-Highways [72] rating systems for buildings and roads, respectively. The lack of use of internal benchmarks can be associated with the fact that they may not provide realistic comparison values, given they do not compare themselves with the built environment [22]. However, they could be used when there is a lack of information on the asset stock and market, or to provide a reference value for a design as seen in the rating systems.

Finally, a hybrid approach can be adopted which combines both external and internal LCA model approaches. For example, Paratscha et al. [53] employed a hybrid benchmarking method, where a model based on "standard service description" (considered state-of-the-art) was used for an internal benchmark (for the target value), and construction reports were used for the creation of external models.

3.2.3. Benchmark approach

Either a bottom-up or top-down approach can be taken for defining a benchmark. Linking to LCA theory, the bottom-up approach would correspond to process-based LCA, whilst top-down would link more to Economic Input-Output LCA (EIO-LCA) [42,63].

The bottom-up approach was the most adopted from the selected studies. This suggests that LCA construction benchmarks are most commonly calculated directly from the case studies. Hollberg, Lützkendorf & Habert [29], Chandrakumar et al. [8] and Bowick, O'connor & Meil [3] state that the top-down approach is more appropriate for target setting or reference values. Specifically, Bowick, O'connor & Meil [3] state that the bottom-up approach is better for whole-building LCA benchmarks, as it is consistent with the method used for energy and water benchmarks, offers the most flexibility, based on real-world estimates of material use, and meets the needs of most common current LCA uses.

On the other hand, the use of top-down by itself was found to be considered in only one study. In three studies, both top-down and bottom-up were combined. Suggesting that when top-down is to be used, it should be accompanied by a process-based bottom-up benchmark too. Häkkinen et al. [26] state that a top-down approach can be largely generic and involve more uncertainty, if the desired product is not directly represented by the industry data. However, in literature this method can be associated with time and cost savings [68], compared to a process-based approach [59].

3.2.4. Database selection

The use of LCA software was most commonly adopted for benchmarking generation. For example, Russell-Smith & Lepech [61], Butt et al. [7], Hollberg, Vogel & Habert [30], Mohammadi & South [46], and Paratscha et al. [53] used a commercial LCA software. Meanwhile, Kamali, Hewage & Sadiq [38] used an open source LCA software. The use of LCA software thus provides the most "ready-to-go" approach to calculating the impacts of the models of interest and generating benchmarks.

Conversely, regarding larger projects with various collaborating institutions, such as in Simonen et al. [65], Pelkmans et al. [55], and Häkkinen et al. [26], primary data was used and a new database was created. Simonen et al. [65] collected life-cycle inventory data from both universities and research institutions, while Häkkinen et al. [26] used case studies of multiple buildings primarily from building consultancies and LCA results from universities and research institutions.

LCIs could also be created through literature review, where Ganassali, Lavagna & Campioli [21] carried out LCAs with impacts collected from material EPDs, and Liu et al. [42] and Iribarren et al. [34] used data provided by the national government. Finally, the rating systems which were found to have adopted benchmarking for buildings, such as BREEAM [6] and DGNB [64], used proprietary data (derived from projects – Fig. 3D). It is important to note that the data quality of the inventory created is also important, and when primary and secondary data are collected for the exercise, a data quality analysis should be considered.

Within the benchmarking study, it is recommended to not only record the impacts of the case studies included, but to also establish a database for the quantities of materials used. As found in the work of De Wolf & Davies [73], the results of an LCA are largely dependent on the impact factors used, plus given that LCAs are currently not harmonised, this factor could prove to be critical for obtaining coherent results. Thus, it was found that through collected data on material quantities, an updateable benchmark database can be created and be revised once impact factors become more accurate with time.

3.2.5. Type of benchmarks

The studies assessed were found to provide benchmark values in various ways, both coinciding and differing from the three benchmark levels defined by the ISO 21678:2020 (i.e., limit, reference and target). This section first discusses the creation of reference benchmark values, followed by the creation of further supporting values (i.e., limit and target values). From Fig. 3E it is possible to see that only 22% of studies would follow the recommended three benchmark levels defined by the ISO 21678:2020.

3.2.5.1. Creating the reference values. According to the ISO 21678:2020, reference values can be represented by either the mean, median, or modal values, by specific percentile values, or by technical and/or economic optimum or feasibility [36]. In a review by Ganassali, Lavagna & Campioli [23], it was found that for buildings benchmarks are typically generated through linear interpolation, statistical analysis or the modelling of a reference building. Hollberg, Vogel & Habert [30] defined benchmarks for various architectural elements (i.e., walls, windows) by calculating the LCA of the components and using the elements' market share to derive the benchmarks. As stated by Mohammadi & South [46], aggregated results should not be provided as simple averages, as this leads to approximations and estimations. Appropriate weightings would need to be applied in order to obtain viable and representative benchmarks. Aggregated and weighted results were also found to be more useable for decision making [49].

Regarding how benchmarks are outputted, Ganassali, Lavagna & Campioli [23] describe how the DGNB and Minergie-ECO present their benchmark values in terms of numbers. However, BREEAM expresses benchmarks in terms of levels (A+ to E) depending on their quantitative scores. While Ganassali et al. describes numerical values to be more useful [22], the latter approach would be better for non-expert users [49]. Furthermore, Nissinen et al. [49] found that non-expert users preferred results to be provided as a single meta-benchmark, instead of various environmental impacts.

Furthermore, according to the ISO 21678:2020, the benchmark reference unit also would have to be declared. In the study carried out by Lavagna et al. [41], the building benchmarks were provided in terms of three reference units: per EU citizen, per dwelling, and per m^2.

3.2.5.2. Limit and target values. Beyond the creation of the reference benchmark value, as previously discussed, the generation of limit and target values would also be required. According to the ISO 21678:2020 standard, limit values can be obtained from statistical analysis, surveys, theoretical calculations, legal requirements, and standards (i.e., from both internal or external models). Meanwhile, target values may be developed by either a top-down or bottom-up approach and from either statistical analysis, surveys, theoretical calculations, pilot projects or policy objectives [36].

In literature, these benchmarks were typically found to be calculated via quartile ranges. Ganassali et al. [21,24], Simonen et al. [65] and Paratscha et al. [53] defined the limit, reference and target boundary ranges according to the higher, inter, and lower interquartile ranges. Meanwhile, Rucińska, Komerska & Kwiatkowski [60] used the standard deviation and Hollberg, Vogel & Habert [30] set more competitive target values at the 0.05 quartile of the available solutions. Alternatively, target values were also found to be calculated from the top-down approach from political targets by Chandrakumar et al. [8].

While the ISO 21678:2020 defines three benchmark classifications, it does indicate that more than one target value may be adopted. Specifically, one target value for short-term targets, and another for long-term ones. This can also be seen to be demonstrated in literature by Häkkinen et al. [26], Paratscha et al. [53], and Bowick, O'connor & Meil [3], where limit, reference (or "business-as-usual"), best-practice, and target values classifications were found. Specifically, a best-practice value would be a short-term goal and target a long-term goal. For example, Paratscha et al. [53] developed a best practice value from a torrent control standard service description (internal benchmark). According to the ISO 21678:2020, the short-term goal would be the higher priority of the two. Rasmussen et al. [57] and Lützkendorf et al. [44] provide a state-of-the-art value as a target value, whereas the ISO 21678:2020 [36] states that a state-of-the-art value should only be used as a reference value. It must be noted that these values would be expected to change over time, just as the performance of built assets would too.

3.3. Defining the general steps required

From the literature review, most studies adopted three key steps for establishing benchmarks, as seen in Fig. 4. The three steps found in these studies were found to coincide with the studies with more steps, where these larger studies were found to have additional sub-steps due to their increased complexity and amounts of data involved.

The three key steps found can be defined as: 1) data collection, 2) LCA of case studies, and 3) benchmark generation. As part of these key steps, further sub-steps could also be considered. Fig. 5 summarises these key steps, along with the pre-defined methodological variables and recommendations for the approach to adopt for LCA benchmarking in the construction sector.

1. **Data Collection**: this first step focuses on the creation of a case study database for benchmarking. Before the database can be created, the goal and scope of the study must be defined. Upon their definition, case studies can start to be compiled. If target values are part of the scope of the study, relevant policy targets are collected too. Upon collating case studies, they are then classified according to the key benchmark parameters of interest, as defined in the scope.

   As part of this step, the following key methodological variables need to be considered:
   a. Study Scope: a large-scale study is recommended for a sector-wide initiative. Under this scope, various case studies should be considered, varying in life cycle inventory and region. Local process-based studies would be less appropriate given they only consider a specific process or case study for one region;
   b. Model Typology: the use of an external model typology (i.e., post-construction) is most recommended, given it would create a more realistic case study database. For a more complete study, these models could also be compared to internal models derived from standards and/or policy targets to create a hybrid typology. However, for sector-wide benchmarks, internal models are not recommended;
   c. Benchmark Approach: a bottom-up approach is preferred for limit, reference and target value benchmark creation, given it being more precise and process specific; despite it incurring further complexity and time requirements. A top-down approach would be required for target values derived from political targets. While this variable is related to the life-cycle inventory, it should be defined within the scope of the study;
2. **LCA of Case Studies**: this step calculates the environmental impact of the case studies. Firstly, a life-cycle inventory (LCI) would be compiled for all products and processes in the case study database (either through data collection or third-party data). Then, the impact assessment would take place to quantify the impacts of each case

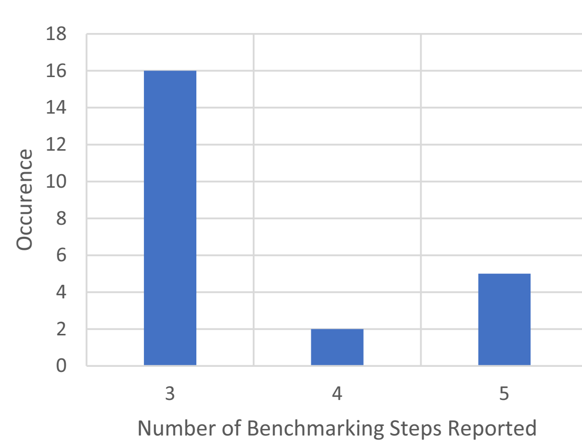

Fig. 4. Frequency distribution of the number of benchmarking steps reported.

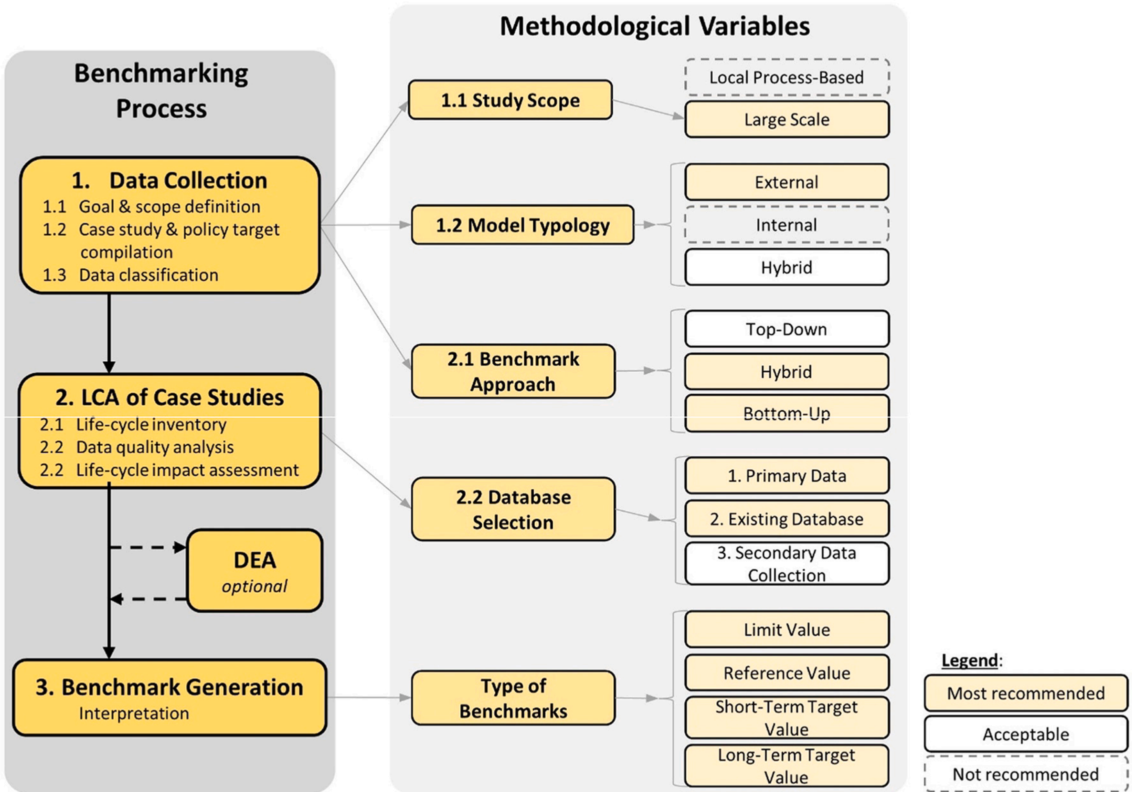

Fig. 5. LCA benchmarking methodology and its associated key methodological variables.

study. The benchmarking database should contain material quantities as well as environmental burdens; to ensure the database's updateability when the product and process impacts are updated [73].

As part of this step, the following methodological variable is considered:

d. Database Selection: as mentioned, the type of LCI would be defined and its values ensured to be appropriate (i.e., for geographical and temporal representativity). To achieve this, a data quality analysis should be undertaken, especially when primary and/or secondary data has been collected, to ensure the validity of the data [55,64].

3. **Benchmark Generation**: this step is similar to the interpretation step for LCA from the ISO 14040 [35], where the LCA outputs are interpreted to define the benchmark values. Thus, this step considers the following methodological variable:

e. Type of Benchmarks: while most studies only provided a single benchmark value, the recent ISO 21678:2020 standard recommends three types of benchmarks should be provided. Namely, a limit, reference, and target value. According to this standard, and in some of the literature reviewed, the target value can take the form of two values: short-term (for state-of-the-art) and long-term (for policy targets). The applicable data sources and reporting guidelines are also stated within the standard.

Finally, data envelopment analysis (DEA) could be added as an additional step after the LCA (Step 2), but before benchmark generation (Step 3). While outside the scope of the majority of the studies evaluated, the use of DEA generates further outputs for benchmarking. Specifically, DEA outputs the relative efficiency of the inputs [11]. DEA is a linear programming methodology used to measure the relative eco-efficiency of entities, and output target environmental impacts for those deemed inefficient. As an example, in the study carried out by Iribarren et al. [34], six LCA impact categories were found for the external walls of buildings, plus the eco-efficiency scores and target impacts from the DEA. In general LCA benchmarking literature, DEA was commonly used when productivity data was used [20].

4. Suggested benchmark pathways for construction products

Fig. 6 provides an outcome-orientated guide for benchmark type calculation, derived from the key steps and methodological variables presented in Fig. 5 (Section 3.3). From the pathways presented in Fig. 6, it is possible to simplify and better interpret the steps required depending on the benchmark type desired. In turn, it is possible to better identify the necessary steps for creating a sector-wide benchmarking initiative for any construction product. A similar key was used as that in Fig. 5, where the most recommended and acceptable actions are indicated. The Study Scope variable has been omitted, given that for the sector-wide methodology explored, only "large-scale" should be explored, and not "local process-based".

Based on the results stated in the previous section, and the pathways in this section, an example process for the creation of a reference benchmark value may be outlined. Firstly, the user would undertake the first step, "Data Collection", as seen in Fig. 5, which involves three steps: a) goal and scope definition, b) case study and policy target compilation, and c) data classification. As part of the first sub-step (goal and scope definition), the user would need to consider three key methodological variables. Namely, study scope, model typology and benchmark approach. As mentioned, study scope may be excluded from this exercise. The user would develop either external or internal benchmarking models; depending on whether the case studies of interest are built case studies or pre-construction models, respectively, or adopt a hybrid model considering both types. Following on, the user would adopt a bottom-up approach for the models defined, which involves a process-based LCA. After having finalised the scope, the user would compile a

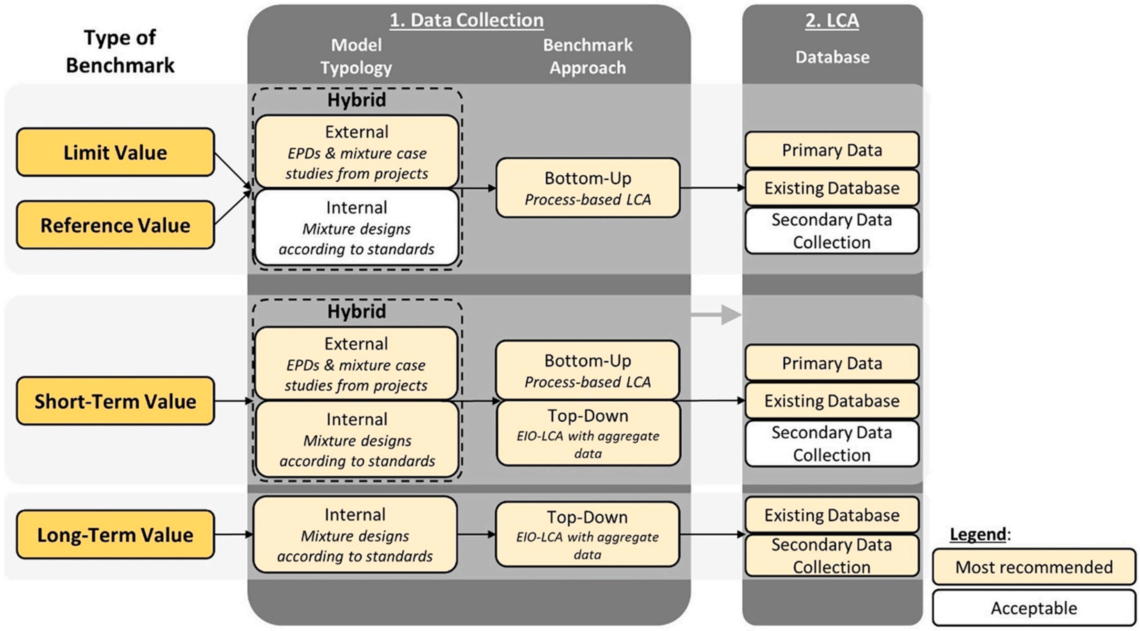

Fig. 6. Suggested benchmark pathways for each benchmark type identified according to the ISO 21678:2020.

database of case studies/models adhering to the defined scope and would classify these according to the key aspects of interest (i.e., region, climate, mixture type, quantity of RAP, etc).

Secondly, the user would undertake an LCA of the case studies/ models in the database created. This key step would be constituted of three sub-steps. Specifically, a) life-cycle inventory creation, b) data quality analysis, and c) life-cycle impact assessment. The inventory compilation stage would consist of the fourth methodological variable identified in Section 3.2: database selection. This variable can consist of either collating primary and/or secondary data, or the use of existing databases. For the development of a large-scale study, the most recommended LCI to develop would be of primary data, specific to the processes constituting the case studies/models collected in step 1. This is because it best represents the processes considered and would provide temporally and geographically representative data. Once the LCI is generated, a data quality analysis should be conducted to ascertain any uncertainties or gaps within it. This would be especially important when using primary and secondary data, where existing databases may already provide this information. Subsequently, the life-cycle impact assessment would be conducted, according to all applicable standards and guidelines for the project (i.e. ISO 14025, ISO 21930 (Part A), and EN 18504), to ensure harmonised impact outputs. It is also suggested that care be taken to report all materials used, so that if LCI updates are carried out in the future, the impacts can also be updated.

Finally, the last step would be carried out for the generation of benchmarks, as demonstrated in Fig. 5. This step is similar to the interpretation phase of an LCA, as defined by the ISO 14040 [35], but with the objective of generating benchmark values. Taking the example described, for a reference benchmark value, the outputs described would be provided per functional unit, according to the PCR considered.

From further analysing Fig. 6, it is possible to identify that limit, reference and short-term values could all be created from a similar methodology. While it is not within the scope of this study to specifically delineate how to generate each value, it can be commented that this can be done in a variety of ways. For example, via mean/median values, specific percentiles, interquartile ranges etc., as seen from the ISO 21678 [36] and various other studies which consider four benchmarks previously referred to in this study [21,53,64].

As a final remark, in addition to the benchmarking approach stated in Fig. 6, some benchmarking studies also included a data envelopment analysis. This step was not frequently found for LCA benchmarking of constructed assets but could be used when the eco-efficiency of processes is of interest.

5. Conclusion

This study aimed to determine a systematic methodology for a sector-wide LCA benchmarking of construction products, via qualitative and quantitative analysis, to encourage the use of more environmentally friendly technologies and decision-making, and in turn, asset management in the construction sector. To achieve this, 23 documents (from peer-review papers and project reports) and 4 standards were selected to be reviewed, including the novel ISO 21678:2020 benchmarking standard on principles, requirements, and guidelines.

Four standards related to benchmarking in the construction sector were found, although none of them are directly linked to LCA. The novel ISO 21678:2020, that has been frequently mentioned in this study, indicates how to report benchmarks, yet there is a need to create a standard methodology for the generation of LCA benchmarks in the construction sector, which can be used towards the achievement of more sustainable practices. It is also necessary to comment that, from analysing the standards with systematic methodologies, benchmarking is a circular process, given that technologies and practices improve over time, so would the benchmark values which have been reported.

From this review, it was found that benchmarking is typically a three-step process: data collection, LCA, and benchmark generation. These steps can be accompanied by various sub-steps, depending on the goal and scope of the study. As part of this three-step process, five key methodological variables were identified to influence the procedure required for generating benchmarks. Namely, these were: study scope, model typology, benchmark approach, database selection, and type of benchmarks. The definition of this set of steps, key methodological variables and the authors' recommendations for the construction sector constitute a first possible LCA benchmarking methodology in this field, which may be applied by the interested stakeholders (i.e., contractors, policy makers and national authorities).

This study has been one of the first to consider the novel ISO 21678:2020, and in turn compare and contrast current benchmarking practices. Future work will apply the benchmarking strategy found, validate the outcome-based pathways identified and defined, and implement the four benchmark types (limit, reference, short- and long-term target values). It will compile over forty case study projects from an international interlaboratory study. The case studies will provide reference values for specific construction products and highlight any potential drawbacks and limitations of the present strategy, in order to further enhance it.

CRediT authorship contribution statement

T. Mattinzioli: Formal analysis, Investigation, Methodology, Writing – original draft. **D. Lo Presti:** Conceptualization, Project administration, Writing – review & editing. **A. Jiménez del Barco Carrión:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

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.

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The author contributions are as follows: Conceptualization, TM., AJBC, and DLP.; Methodology, TM and AJBC; Data Collection, TM; Formal Analysis, TM; Writing—Original Draft Preparation, TM; Writing—Review & Editing, TM, AJBC, and DLP; Project administration, AJBC and DLP.

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Appendix A: Summary of Studies Considered

Table 2 displays the selected studies according to the methodological variables identified. The studies are presented per study size and in chronological order.

Table 2
Summary of benchmarking methodologies found in selected construction sector literature.

Study scope	Model typology	Benchmark approach	Inventory	Number of benchmarks	Number of steps	Reference
Local Process-Based	External: data from construction plan.	N.A.	3rd Party - commercial: SimaPro with Ecoinvent 2.2	**1**: benchmark impact line to follow during construction	**3** 1. Analysis of construction plan; 2. LCI of individual activities; 3. Creation of benchmark impact line.	[61]
	External: field investigations with local contractors & experts	Bottom-Up	Project Specific: Local sector-specific LCI	**1**: reference	**3** 1. Case study definition; 2. LCA; 3. Benchmark creation;	[62]
	External: data from airport.	Bottom-Up	3rd Party - commercial: GaBi w/ local electricity mix calculated	**1**: reference	**3** 1. Case study definition; 2. LCA; 3. Benchmark creation;	[7]
Large-Scale	External: 7 countries	Bottom-Up and Top-Down	Project Specific: from 13 institutions	**4**: limit; reference; best-practice; target.	**3*** 1. Definition of assessment method for indicators 2. Definition of functional equivalent and rules for comparison 3. Definition of benchmark values	[26]
	External: 25 wind farms	Bottom-Up	3rd Party - commercial: Ecoinvent	**5**: reference; efficiency; operational reduction; impact reduction; economic saving	**5** 1. Definition of case study (process, area & boundary conditions) 2. LCA + DEA framework 3. Inventory assessment (materials and impact comparison) 4. DEA performance (efficiency scores, operational reduction percentages, and target environmental characterisation)	[33]

(continued on next page)

Table 2 (*continued*)

Study scope	Model typology	Benchmark approach	Inventory	Number of benchmarks	Number of steps	Reference
					5. Interpretation (material & economic savings and efficiency generated)	
	External: 13 Peruvian anchoveta steel and wooden fleets	Bottom-Up	3rd Party - commercial: Ecoinvent v2.2 in SimaPro v7.3	**2**: average values per case; eco-efficiency scores	**5** 1. Data collection 2a. LCIA 2b. DEA input definition 3. DEA computation 4. benchmark case studies 5. eco-efficiency interpretation	[2]
	External: 175 external walls	Bottom-Up	3rd Party - national: Ökobau.dat database, German Federal Ministry of Transport, Building and Urban Development	**2**: reference impact for 7 impact categories; eco-efficiency score.	**3** 1. Data collection 2. LCA 3. DEA	[34]
	External: 23 cases from Ministry of Education Science and Technology	Bottom-Up	3rd Party – national: Country-specific hybrid LCA model	**1**: defined through statistical analysis (i.e. homogeneity test and correlation analysis)	**3** 1. Case study data collection 2. LCA 3. Benchmark creation	[37]
	External	Bottom-Up	Literature Review: Building EPDs collected from European EPD Program Operators	**3**: limit; reference; target.	**4** 1. Set LCA benchmarks from EPDs 2. Integrate benchmarks to GPP 3. Methodology for buildings elements 4. Methodology for whole buildings	[21,24]
	External: data provided by cement, aggregates and concrete industries	Top-Down	3rd Party – commercial: GaBi 7.2.2 software and dataset	**1**: normalised environmental impacts	**5** 1. Definition of products, processes and impact categories 2. LCA 3. Presentation and interpretation of results 4.Normalised impact benchmarks 5. Data quality, limitations, variation of results and sensitivity analysis	[46]
	External: 1191 building LCA studies	Bottom-Up	Project Specific: 18 sources (structural engineering firms; institutes; applicable databases; data of research team).	**3**: median and inter-quartile ranges	**5** 1. Data gathering; 2. Data quality assessment; 3. Aggregation; 4. Classification; 5. Analyses	[65]
	External: rating system project data	N.A. as from building rating system	Project specific: internal data from BREEAM rating system	**1**: self-defined “ecopoint” indicator	**3** 1. Data collection 2. Data separation per building type 3. Benchmark indicator calculation.	[6]
	External: building stock data from [18], [17], [67], [13], [51], [14], [4]	Top-Down and Bottom-Up	3rd Party – commercial: SimaPro 8.3 software with Ecoinvent 3.2 database	**1**: average reference value	**3** 1. Development of models based on housing stock data 2. LCA 3. Analysis of results	[41]
	External: 5 multi-family constructions	Bottom-Up	3rd Party – national: Embodied impacts from Ökobaudat. Building energy consumption from local energy provider.	**1**: GWP	**3** 1. buildings and strategies selected and primary energy balance assessed; 2. LCA benchmarks defined and compared to target; 3. LCA compared with LCC with Pareto method	[10]
	External: 3 Canadian building case studies	Bottom-Up	3rd Party – open access: Athena LCI	**3**: single index values calculated (EPA, BEES, and equal) from 8 impact categories	**3** 1. Definition of case studies; 2. LCA; 3. Establish benchmarks and compare impacts (AHP normalisation)	[38]
	External: Shanghai Building Materials Market Management Center	Bottom-Up	3rd Party – national: Chinese Life-cycle Carbon Emission Factor Database	**1**: reference.	**3** 1. Definition of production process;	[42]

(*continued on next page*)

Table 2 (*continued*)

Study scope	Model typology	Benchmark approach	Inventory	Number of benchmarks	Number of steps	Reference
					2. LCA; 3. Benchmark generation.	
	External: components defined in BKP-H (Baukostenplan Hochbau)	Bottom-Up	3rd Party – commercial: Ecoinvent v2.2	**4**: min; mean; max; 0.05 quartile.	**3** 1a. Create structured list of building components and their impacts 1b. Determine components' market share 2. Weight the impact of a product according to component market share 3. Calculate benchmark with lognormal distribution	[30]
	External: 28 Italian and 7 Danish buildings	Bottom-Up	3rd party – national & commercial: Embodied impacts: CasaClima (IT) & Danish Green Building Council (DK). Plus, use of: Ecoinvent in Excel and GEN_DK in LCAbyg 3.2.	**3**: total, embodied and operational benchmarks, plus IQR.	**3** 1. Define case studies; 2. LCA; 3. Benchmark classification; 4. Methodological comparison.	[57]
	Hybrid: internal from standard & external from structure types	Bottom-Up	3rd party – commercial: Ecoinvent 2.2, supported by [19]	**4**: limit; reference; target; "standard service description"	**4** 1. Definition of functional unit and structure types 2. Definition of system boundaries 3. Definition of benchmarks 4. LCA uncertainty assessment	[53]
	External	Bottom-Up	Project Specific: Internal data from DGNB rating system	**3**: reference; limit; target.	**5** 1. Template creation 2. Data sorting 3. Harmonised database generation 4. Data quality assessment 5. Benchmark creation	[64]
	External: three New Zealand case studies and BRANZ building stock projection	Bottom-up for climate impact; Top-down for climate target	3rd Party – open access: Climate impact: LCAQuick v3.3; Climate target: BRANZ	**2**: total impacts and targets.	**3** 1. Definition of case studies and sector building stock; 2. Climate target 2a. determine max global GHG emissions 2b. Assign country share based on population 2c. Assign share to construction sector 2d. Calculate target for building categories. 3. Compare building stock and targets	[8]
	External: literature assessment f 656 building case studies	LCA not carried out, only analysis of other studies	Project Specific: Impacts obtained from case studies	**2**: embodied and operational carbon, plus their IQRs. Results compared to Swiss SIA 2040 benchmark.	**3** 1. Compilation of case studies; 2. analysis of embodied GHG emissions; 3. comparison with Swiss SIA 2040.	[58]
	External: 11 office buildings	Bottom-Up	3rd Party – commercial: Energy need: Design Builder; LCA: OneClickLCA.	**4**: limit, reference, best-practise and target values.	**3** 1. Case study defined; 2. LCA; 3. Benchmark creation.	[60]

* Focused on sustainability performance assessment benchmarking as well as LCA.

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