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*Review*

# Life Cycle Assessments of Circular Economy in the Built Environment—A Scoping Review

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**Abstract:** The Circular Economy (CE) is gaining traction throughout all industries and nations globally. However, despite several attempts, no one-off solutions for assessing the benefits and pitfalls of CE have been established, and neither have any measures with which to determine decisions. In line with this general observation, the Built Environment (BE) is no different. A tendency is observed in which, for the assessment of the environmental impacts of CE, a Life Cycle Assessment (LCA) has been deemed suitable. This paper presents a scoping review, using the PRISMA statement extension for scoping reviews, documenting how LCA has been applied for assessment of CE in the BE. The review covers a broad scope of literature, scoping the landscape, and delimits it into publications where CE strategy has been defined explicitly and described as a CE investigation. Among the LCAs applied, the dominant system boundary choice is the attributional approach. The authors open the discussion on whether this is actually suitable for answering the questions posed in the CE paradigm. From the review, and the discussion, the conclusion suggests that there is no dominant procedure in applying LCA of CE in the BE, even despite commonly developed LCA standards for the BE. Few studies also present the consideration to reconsider the applied LCA, as CE puts new questions (and thereby a potentially greater system boundary, as CE may imply greater societal consequences) that do not necessarily fit into the linear LCA framework currently applied in the BE.

**Keywords:** circular economy; life cycle assessment; built environment; construction industry; methods and scope; scoping review

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## 1. Introduction

In relation to the transition from a Linear to a Circular economy (CE), the discussion on how to assess the benefits and pitfalls is ongoing. Many considerations must be taken into account when aiming at transitioning into a CE, and if they are not properly assessed, CE solutions may not necessarily lead to more sustainable solutions. When considering the main definition of sustainability, historically, the triple-bottom-line is often highlighted, taking into account the balance between the social, economic, and environmental impact dimensions. Acknowledging the importance of considering all aspects of the triple-bottom-line for sustainability, this paper looks deeper into the environmental aspects, investigating the application of environmental assessments of CE solutions within the BE. Whereas environmental assessments through life cycle assessments (LCA) have been applied in a somewhat straightforward way to the linear economy, the questions asked when transitioning into a CE present a new complexity as well as the importance of considering potential unintended consequences and possible rebound effects.

This review aims to assess the extent to which the approaches applied to answer questions regarding the economic model and environmental performance of the BE are transparent, consistent, and in accordance with the general EU recommendations [1], when considering the appropriate scale of the decision support applicable to the different types of LCAs of building principles and economic models. Although most LCA assessors are aware of the existence of the EU recommendations [1] regarding the valid decision context associated with the types of LCA, it appears that the majority of the assessments in the BE stick to the classical and simplistic way of performing building LCAs (i.e., attributional LCA (ALCA) applying the cut-off system model, in concordance with the construction coherent standards, i.e., EN15804 and EN15978 [2,3]). The results of these assessments are most often correctly used to judge the environmental performance of building principles and economic models seen from a single building perspective, and are often subsequently—and incorrectly—used to make recommendations on how the environmental performance of the society benefits from these building principles and economic models. Some authors have already described this potential misalignment, e.g., [4,5]; however, a systematic overview and analysis of the problem, with the BE specifically as a focus, seems to be lacking.

The study is performed as a scoping review, following the PRISMA statement extension for Scoping Reviews [6,7]. Scoping reviews are primarily known within health sciences, and a search indicates that only a few studies related to construction have been published, e.g., [8–11]. Considering the vast amount of methods available to conduct a knowledge synthesis, several methods were considered for investigating the objectives of this review, e.g., Systematic Review, Rapid Review and Scoping Review. Based on Munn et al. [12], the scoping review approach was chosen rather than the systematic literature review, as the study seeks to investigate the landscape and map out available evidence within the use and application of LCA of CE in the BE.

*Objectives*

This study presents a Scoping Review (ScR) and aims at investigating the following main research question (RQ): What are the questions we pose in terms of the scale dependent environmental performance of building principles and economic models, and how do we answer these questions LCA-wise?

Building principles are, in this context, defined as building/urban/construction/civil engineering designs/concepts/technologies, exemplified as buildings, neighbourhoods, building components or elements, but also road construction and infrastructures, and for all types of construction materials, or even raw materials. By 'environmental performance' in this study, is meant the performance/action in relation to environmental impacts of a given action/service/product, etc. The impacts are resultant of emissions or the use of resources, quantified through an LCA. Thus, the scope of the assessments in the reviewed papers must consider impacts on the environment caused by emissions or resource use, i.e., omitting studies that solely assess other environmental 'impacts'. Examples on omitted topics are, e.g., noise/acoustic pollution, health, air quality etc., thus impacts that are not induced by specific (energy, molecular, atomic etc.) elementary mass flows. Economic models are, in this context, defined as the business-as-usual (BAU) linear economic models and the circular economic (CE) models applied in the BE.

The research question of the paper can be further sub-divided into three main sub-aspects: (1) Environmental performance assessment approaches applied to building principles, (2) Environmental performance assessment approaches applied to economic models and building principles, and (3) LCA approaches applied to building principles and their economic models (e.g., scope, methodology and how conclusions are drawn from the studies)

The first subject has been widely assessed in recent decades, which leads to the exclusion of the generic search on "Environmental performance approaches on building principles". Examples of recent review papers within the 'building principles' area are, e.g., [13–16]. The second and third sub-aspects are addressed in the literature search covered by the paper, however, with specific limitations.

The purpose of the scoping review (ScR) is to identify what questions are posed regarding the environmental performance assessment of building principles and economic models and what LCA choices (i.e., of system boundaries/models, dynamics/temporal scenarios, and impact assessments) are made to answer these questions.

By answering this narrowed purpose, we aim at defining the progress of the research stream and highlighting the application of methodologies, thus enabling a clear framing and recommendations on future research. Due to the temporal limitation of the study and the vast amount of studies performed on 'environmental assessments' this review has been limited to focus on the application of LCA to investigate its environmental impacts. Attention is only given to studies explicitly addressing circular economic models, as most systems not defined specifically into e.g., CE, are assumed to be conventional linear economic models (though most often presented without proper categorization).

While the number of published works addressing CE is increasing rapidly, reviews performed on the existing literature are still limited. Benachio et al. (2020) [17] performed a review focused on the circular economy and buildings (with a delimiter of also applying reuse, case of technique) that aimed at mapping how CE is used in the construction industry. Benachio et al. (2020) divided the work found into the following six areas of research: development in CE, reuse, material stocks, CE in the BE, LCA and material passports, and concluded research gaps in every area, e.g., in LCA, where the assessment method for considering CE concepts needs development [17]. Çimen (2021) [18] addressed development trends and literature maturity in the field, finding that a substantial amount of the work published had been conducted in China and concluding that the most studied subjects were waste valorisation and CE promotion/transition, along with materials being the most studied scale and urbanor building scale less so [18].

Hossain & Ng (2018) [19] performed a review of LCA performed on buildings, covering surveys, reviews, and case studies, demonstrating research gaps for comprehensive building assessments. In addition to the review, they propose a framework for assessing CE implications, focusing on the little-covered aspects of resource-efficient buildings and resource recovery [19]. Lovrenčić Butković et al. (2021) [20] looked into the tools and assessment methods used for evaluating CE in the construction industry, aiming to categorize CE concepts and tools used for assessments. They found, like other studies, that the number of environmental performance assessment studies is increasing, and that the most frequently applied assessment tool is LCA, along with the most often assessed life cycle stage being waste management [20].

Not addressing CE in the BE directly, but nonetheless covering construction and demolition waste (CDW), which is inherently a significant aspect in the CE agenda, López Ruiz et al. (2020) [21] investigated the key strategies of CE in CDW, and the assessment methods of the emerging research area, concluding that 36% of the included studies were approached from an environmental perspective. They introduce a framework, emphasizing waste management and the recirculation of recovered materials, amongst the 14 defined strategies [21].

Ghisellini et al. (2018) [22] reviewed how selected CE R-imperatives (i.e., Reduce, Reuse and Recycle) apply to CDW management and how the environmental impacts and economic costs can be influenced. Ghisellini et al. (2018) find that most assessments are performed through LCA and show a beneficial tendency in reductions, nonetheless highlighting the site specificity of existing studies [22]. Colangelo et al. (2020) [23] performed a comparative LCA study on CDW used in concrete, however, through a preliminary review on state-of-the-art literature, Colangelo et al. (2020) assessed existing studies in the same field, looking at materials assessed, the system boundaries (finding that most studies were performed as cradle-to-grave studies), and impact assessment methods (which did not conclusively use a dominant method). Colangelo et al. (2020) conclude on a central issue in the consistency of the assessed studies in the use of different functional units [23].

Taking a broader view, Larsen et al. (2022) [24] looked into how CE is assessed more holistically through the integration of LCA, LCC (Life Cycle Costing), and S-LCA (Social-

LCA). They found that only 13 of the included 42 articles report on all three methods, and that in order to transition into CE properly, the integration of methods needs development, with S-LCA especially needing further maturation [24].

Lei et al. (2021) [25] conducted a literature review with the aim of addressing how LCA is applied in the context of CE and BE, with the aim of providing a proposal for the transition of the BE into a sustainable future through a discussion on enablers and barriers to application [25]. While the questions asked in our scoping review partially align with the reviewed topic from Lei et al. (2021) [25], the main question asked by Lei et al. and ourselves differs. Instead of looking at the enablers and barriers when applying LCA on CE in the BE, we ask 'what questions are we seeking to answer' when using LCA to assess CE in the BE.

This scoping review does not aim to be an exhaustive study but rather to map out the existing research and the state-of-the-art knowledge, within the research questions posed above. The literature search thus applies a very specific set of phrases, including, partially, the large amount of predecessing terminologies of the Circular Economy as defined by the schools of thought of the Ellen MacArthur Foundation [26].

## 2. Method

The scoping review at hand is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews, PRISMA-ScR [6]. While an update of the PRISMA statement (called the PRISMA 2020 statement) was published in 2021 [7,27] recommending existing PRISMA extensions to be updated to reflect PRISMA 2020, the extensions for scoping reviews have not been updated since 2018. Thus, the review is reported in accordance with the PRISMA 2020 statement [7] coupled with the specific guidance given in [6].

The scoping review is mainly based on the checklist given in PRISMA-ScR [6]. The PRISMA 2020 checklist [7] contains 27 items, divided into 7 sections. Some of these items are not relevant for a scoping review, as explained in the checklist and appendix of Tricco et al. (2018) [6]. From this, the checklist, and thereby the steps and inclusions to the scoping review, are interpreted as shown in Figure 1.

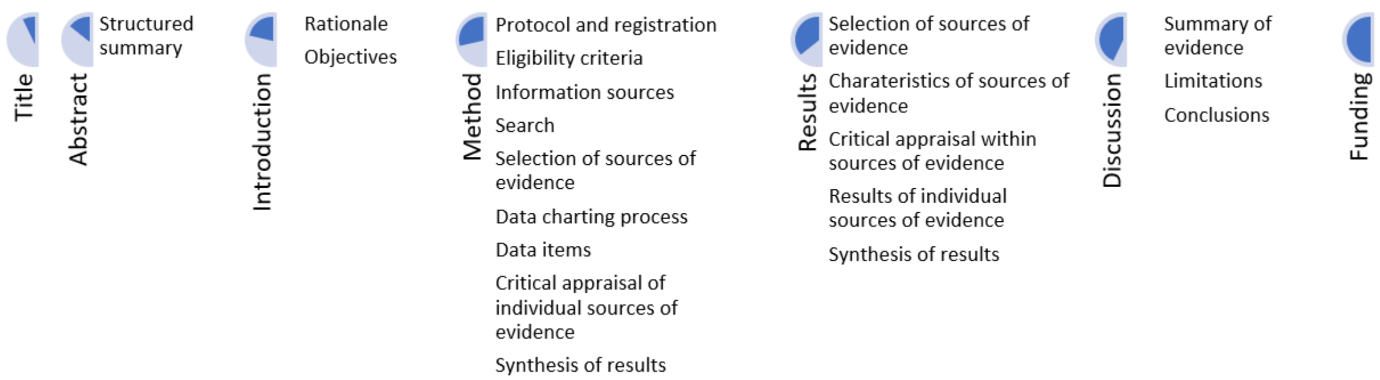



**Figure 1.** Interpretation of the included steps, based on the PRISMA extension PRISMA-ScR [6], to conducting a scoping review in the coherent review.

Whereas some of the PRISMA steps are merely reporting structures (see Figure 1, noted as 'headers'), some sections are found helpful as a stepwise contents structure. Thus, the single items in the methods and result section follow the item structure from PRISMA-ScR neatly, enabling the ScR to be replicable through structure and transparency.

The following sub-sections describe the methodological process of performing the scoping review, including selection criteria for inclusion and search iteration steps. As the scoping review covers a large body of literature, and thus several search iterations and delimitations, the conceptual process and terminology is shown in Figure 2. The detailed exclusion/inclusion workflow is illustrated in Figure 3.

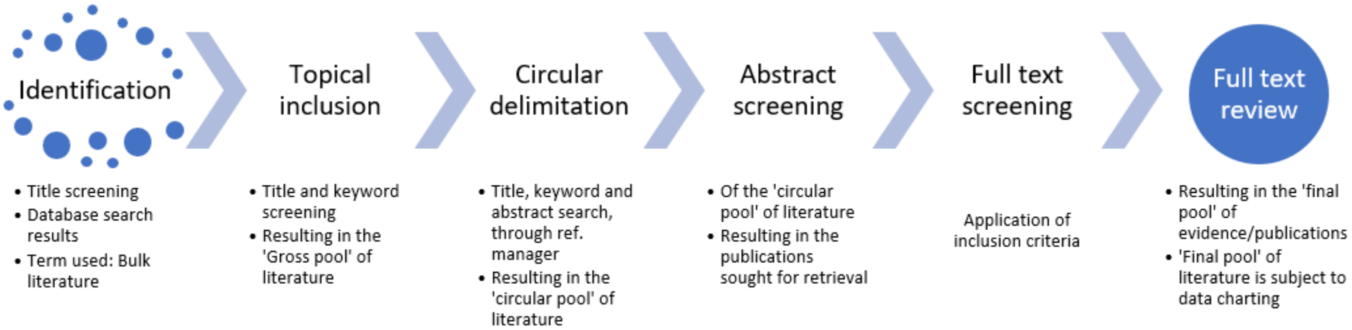



**Figure 2.** Conceptual process and terminology applied in the processing of search results and sorting for eligibility.

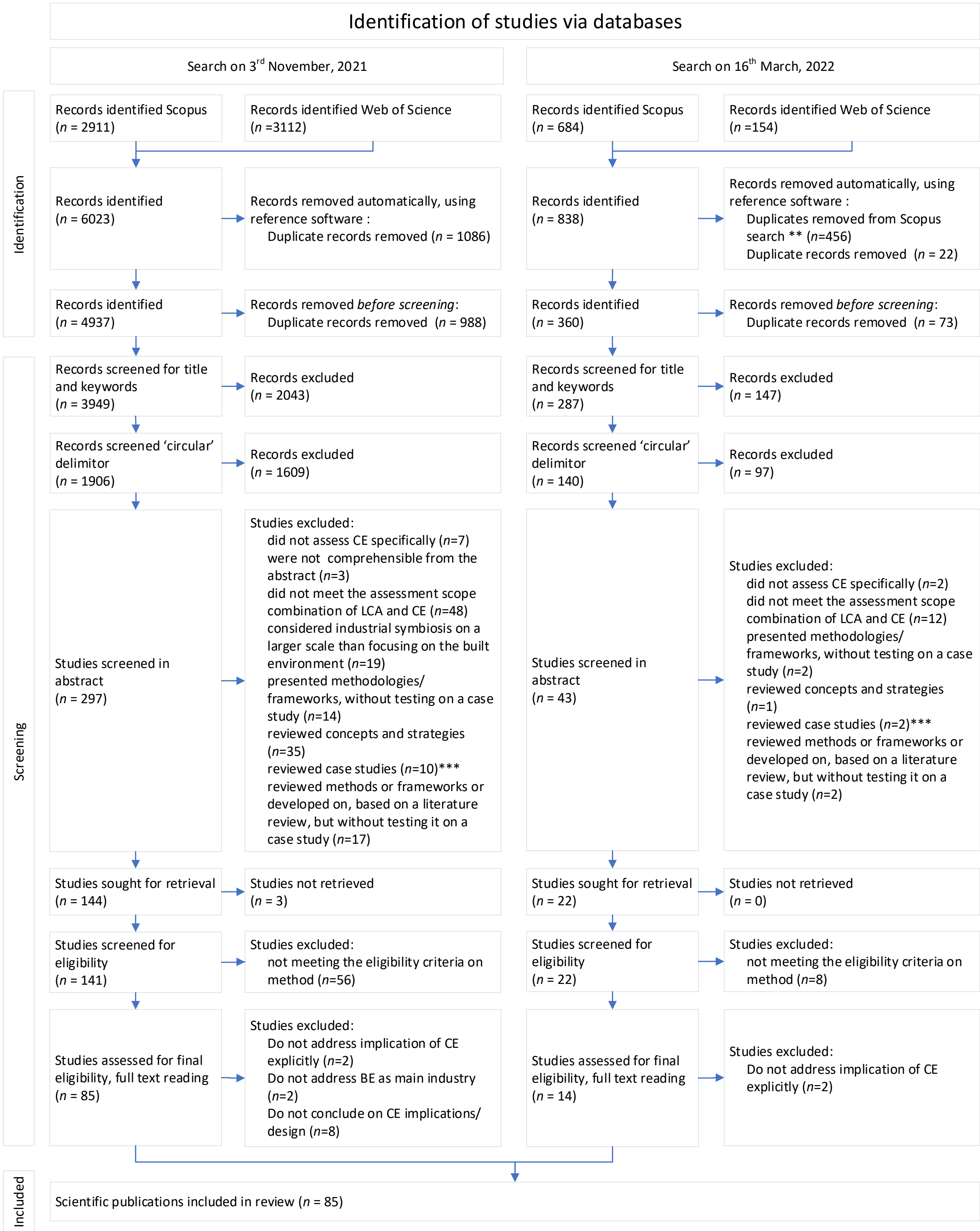



**Figure 3.** Flow diagram for the scoping review process, on included searches of databases, based on the PRISMA 2020 template (Page et al., 2021) [7]. ** = due to lack of temporal limitation detail possibilities, *** = this pool was screened for perspectives.

## *2.1. Protocol and Registrations*

No protocol exists apart from the descriptions in the following sections. They were formulated early in the process in order to discuss the process among the authors.

### 2.2. Eligibility Criteria

The ScR assesses scientific publications by considering their content qualitatively, as the quantitative results are not considered relevant at this stage (as e.g., no reference study values are relevant to determine areas of future research). However, quantitative assessment must be performed in the included studies in order for the qualitative review assessment to be performed.

The general inclusion criteria for the included literature are:

- A study must assess circular economy (or one of the defined search synonyms, or predecessing concepts).
- A study must contain assessment of environmental performance. It must have narrowed the assessment method to an LCA.
- A study's environmental assessment must cover at least 1 building principle within a given circular economic model/strategy (explicitly or implicitly defined).
- A study must provide sufficient detail on the applied assessment method, i.e., how the assessment has been applied, which LCA approach and system boundaries were applied, and what impact assessment methods were used and the decisions/-support derived from the assessment.

In order for a scientific paper to be included, it is further required to:

- be peer-reviewed
- be in English, Danish, or German

A temporal limitation is applied from 2012–2022, based on the temporal scope of work by the Ellen McArthur foundation, where their first report was published [28].

### 2.3. Information Sources

The searches for scientific literature have been performed using electronic search engines for scientific/academic papers: Web of Science and Scopus (for cross-checking).

The search strategies were discussed with experienced librarians at the university library of University of Southern Denmark and refined through discussions among the authors and supervisors. The final search strings combinations applied in Web of Science and Scopus are presented in Table 1.

**Table 1.** Search strings, using the applied keyword synonyms as presented in Table 2. Asterix (*) in the search strings, indicate the use of the wildcard function in searches.

| Search Strings |
|---|
| LCA OR "life cycle assessment*" OR "life cycle analy*" OR "lifecycle assessment*" OR "lifecycle analy*" |
| "circle econom*" OR "circular econom*" OR "linear econom*" OR CE OR circularity OR "industrial ecolo*" OR "cradle to cradle" OR C2C OR "performance econom*" OR biomimic* OR "natur* capital *" OR "regenerative design*" OR "blue econom*" OR refus* OR rethink* OR recov* OR reus* OR repair* OR reman* OR refurb* OR recycle* OR renovat* OR "resource econom*" OR "eco design*" OR upcycle* |
| "Built environment" OR building* OR constructi* OR "building design*" OR "building system*" OR "civil engineering" OR built* OR urban* OR communit* OR city OR cities OR infrastruc* OR neighborhood OR neighbourhood OR district OR region OR "building stock*" OR "housing stock*" OR "dwelling stock*" OR "built struct*" OR landscap* |

The selection process has been illustrated in Figure 3, presenting the refinement steps and iterations performed on the bulk literature results extracted from the electronic search engines/databases. These steps were performed in order to reduce the number of studies to be analysed and included to a number that could be practically handled.

Whereas the search strings and combinations were iterated throughout the Fall of 2021, the final search string combination was applied ultimo 2021. In order for the scoping review to contain most recent published literature, the search strings were periodically applied on the same databases to see if new research had been published since the initial search. The last updated search was performed on 16 March 2022.

### *2.4. Search*

The search phrases applied were based on a specific set of keywords derived from the RQ and their synonyms, see Table 2.

**Table 2.** Applied keyword synonyms for search strings.

| Key Word | Applied Search Synonyms | | | | |
|---|---|---|---|---|---|
| *Environmental performance* | LCA | Life Cycle Assessment | Life cycle Analysis | Life-cycle Analysis | Lifecycle analysis |
| *Building principles* | Built Environment | Building | Construction | Building design | Building system |
| | Civil engineering | Built | Urban | Community | City |
| | Cities | Infrastructure | Neighbourhood | Neighborhood | District |
| | Region | Building stock | Housing stock | Dwelling stock | Built structures |
| | Landscape | | | | |
| *Economic models* | Circle economy | Circular economy | Linear economy | CE | Circularity |
| | Industrial ecology | Cradle to cradle | C2C | Performance economy | Biomimicry |
| | Nature/-al capitalism | Regenerative design | Blue economy | Refuse | Rethink |
| | Recover | Reuse | Repair | Remanufacture | Refurbish |
| | Recycle/-ing | Renovate/-ion | Resource economy | Eco design | Upcycle/-ing |

To obtain focused and relevant results, the search strings were targeted at the publications' titles, abstracts, and keywords, using 'Topic' and/or 'Title' field tags in Web of Science and Scopus.

The applied search strings are shown in Table 1. By combining the three search strings, through Boolean operator "AND", the final search was established, and concurrent numerical results/findings of the searches in the databases are presented in Figure 3.

Throughout the search string iterations, leading up to the strings in Table 1, some keyword synonyms were revised, as they were found to skew the pool of results, and therefore they were excluded in the final search strings presented in Table 1. In particular, the use of CE R-imperative 'Reduce' can be highlighted, which is a word commonly used in the assessment of environmental impacts. Another is 'industrial symbiosis' (IS), as this is often not directly related to the BE but has a broader scope, though it is interesting in the greater scope. An interesting study, which included IS in its review but did not consider the BE and construction, as these are seen as specialist topics, is Harris et al. (2021) [29]. They reviewed the most recent literature within CE and assessment of environmental implications, dividing systems at micro (product), meso (industrial), and macro (national or city) level, finding that few studies link the impacts between levels (e.g., product and societal consequences) [29].

### *2.5. Selection of Sources of Evidence*

The identification of the bulk literature (raw output from the searched databases) was processed through EndNote [30] by exporting the search results from Web of Science and Scopus.

The bulk literature was checked for double appearance throughout the two databases using the referencing software 'duplicates' function, screening for respectively 'author'/'title'/'year' and 'title'/'year' comparisons, ignoring spacing and punctuations. A manual screening was additionally performed (few title duplicates remain, due to double publication with altercations from conference proceeding to journal article) by the main author.

After the identification process and the removal of duplicates, the remaining pool of papers were screened on titles and keywords for topical inclusions conforming with the listed criteria. Here, studies on, e.g., indoor environment, municipal waste management systems, refinery and energy processes and systems, farming, behavioural patterns and health, consumer goods and services, transportation systems, and offshore structures were excluded. This screening resulted in a 'gross pool of literature'.

An additional delimitation was subsequently performed on the gross pool of literature, singling out all references addressing the term 'circular' explicitly. This step was performed for the content of the review to be comprehensible, enabling practical handling of the scope of the review. This delimiting step is included in the review halfway through instead of at the starting point in order to map out some initial tendencies in the gross pool of literature. By further applying a criterion for the papers to contain 'circular', the gross pool of papers was reduced to the 'circular pool' of literature, which were subject to an abstract screening. All papers screened on abstracts were included in a separate excel sheet, noting the reason for exclusion. The publications included from abstract screening were subject to being sought for retrieval.

Of the publications retrieved, a full text screening was performed, applying the inclusion criteria for the full text screening by checking for methodological and data comprehensiveness. Criteria for inclusion are: (1) an LCA foreground system must consider aspects of the Built Environment as primary focus, (2) quantification of CE solution, resulting in a conclusion if CE pays of (yes/no).

If a paper was included for full text review, complying with the inclusion criteria, computer commenting in the PDF was used, highlighting, e.g., sections for extraction.

### 2.6. Data Charting Process

A preliminary data-charting form, for extracting data from the final pool of literature, was developed by the main author and supplemented by the co-authors (see the next section). All papers in the final pool of literature were read in full length before charting data due to the possibility of iterative data charting and questions, thus enabling a more holistic and consequential extraction for processing in the results section. The data were charted using an extraction setup in Excel, based on the notes and highlights marked for extraction in the text PDF.

### 2.7. Data Items

The preliminary data charting items are shown in Table 3, and the additional ones added throughout full text reviews are shown in Table 4.

**Table 3.** Preliminary data charting items.

| **Author** | |
|---|---|
| Year of study | Temporal trends |
| Title | |
| Type of paper | Methodology, case study or review |
| Aim of study | Method development, proof of concept, decision support etc. |
| Main focus of study | Only LCA, or technical performance, mechanical test etc. |
| Region/country of main author | Spatial trends |
| Journal | |
| Scale of case | |
| Region of case | Spatial trends |
| Temporal trends | Reference year, RSL or Reference study period |
| Subject of study/case/stock | material, building, etc. |
| Definition of CE | Concept studied (e.g., R-imperative) |
| LCA reference | Standard, guidelines, etc. |

| | |
|---|---|
| FU/DU | what's the functional or declared unit? |
| Life cycle scope | e.g., embodied, operational, full |
| Life cycle approach | ALCA, CLCA, etc.? What def. of the methods is used? |
| System boundary | How are secondary functions and/or co-products handled? |
| Life Cycle stages | process level or according to EN15804/EN15804 |
| System boundary, content | Life cycle stages and processes included |
| Background LCI data | Ecoinvent, GaBi, |
| PS modelling software | OpenLCA, GaBi, SimaPro, national programme etc. |
| EoL inclusion | How do they project—static or prospectively |
| LCIA method | e.g., CML, ILCD etc. |
| Environmental indicators | GWP, AP, Resources, etc. |
| Normalisation and weighting | yes/no, how? |
| Interpretation approach | e.g., MCDM, |
| Does CE pay of? | |

**Table 4.** Additional data charting items.

| Type of Publication | Conference Proceeding, Journal Article |
|---|---|
| Products compared | functionally equal compared or the same product |
| CE cycles | Number of e.g., reuse cycles assessed/ |
| CE assessed | e.g., closed, or open loop recycling, and up front or prospective CE |
| Allocation method | |
| LCI foreground data | BIM, manufacturers, literature, etc |
| Sensitivity analysis | yes/no, how and what? |

### *2.8. Synthesis of Results*

The studies were grouped according to type of study, but with an overarching requirement that they must contain at least one CE quantifying case study. Review studies were not included in the pool of papers directly, unless a quantifying case study was used for perspective.

## 3. Results

### *3.1. Selection of Sources of Evidence*

The selection process was performed over several steps due to the bulk nature of the search results (see the flow diagram for the process in Figure 3. In total, the included papers for review, amount to 85 peer-reviewed papers, synthesized through the note and data extraction matrix.

### *3.2. Characteristics of Sources of Evidence*

The study characteristics of the 'final pool'/included scientific publications for the full review are shown in Table A1, Appendix B, covering qualitative characteristics. For publications used for synthesising the pseudo tendencies in the gross and circular pool of literature, the total list of titles (2046 and 340 titles respectively) can be obtained upon request.

### *3.3. Results of Individual Sources of Evidence*

*The relevant data that were charted, relating to the review questions and objectives, are found in Table A1 (Appendix B) and further in Supplementary Materials, divided per study (covering*

*Case study characteristics (Table S1) and LCA characteristics (Table S2)).3.4. Synthesis of Results*

3.4.1. Synthesis of Preliminary Search Process and Screening

This step is performed in order to assess overall but pseudo tendencies in the pool of studies, compared to the final pool of included studies. The inclusion overview is intended to give a perspective between the final included studies relative to the gross pool and circular pool of literature which was screened throughout the scoping review. From Figure 4, it is seen that the temporal trend of publication changes. Looking at the left hand figure, which covers 2046 titles, but also a broader scope of keywords surrounding CE (cf. Table 2), the number of published papers is already prominent in 2012, whereas, when limiting the focus to studies containing 'circular' specifically (middle diagram), this number is reduced considerably, and the publications are found to start taking off in 2016. Looking at the right-hand figure, considering only the final pool of included studies (85 titles), a similar trend to the 'circular' is found, with an increasing amount of papers since 2016. This is in line with previous finding in e.g., [18].

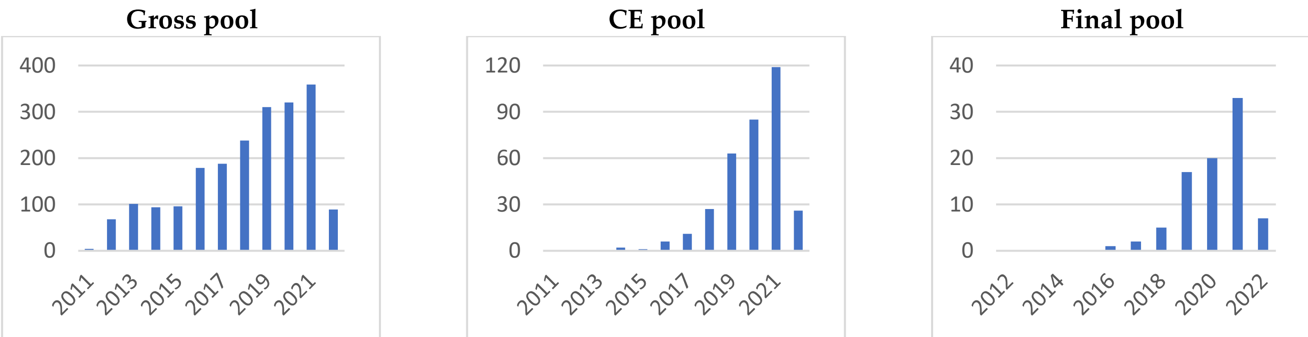



**Figure 4.** Temporal trends, year of publication. The vertical indicator does not have the same values, e.g., changes with a factor 10 from left to right, due to the included quantity of papers. **Left**: Gross pool of relevant literature, including CE predecessor keywords, **Middle**: pool of literature, delimited to contain 'circular' explicitly, **Right**: final, and included, pool of literature.

When looking at the applied search string keywords/synonyms from Table 2, in Figure 5, the trend in topics change for some, but not all. The synthesis of trends must be read with caution, as they are used for mapping out a preliminary understanding of the search field.

Looking at Figure 5A, it is seen that most search string keyword synonyms appear in the same frequency (measured as % of the total in each pool, respectively) across the delimitation iterations, with, however a few exceptions: circular economy, circularity, reuse, repair, refurb, and renovate. Whereas the first two mentioned are inevitable, considering the delimitation of 'circular', the use of different R-imperatives presents an interesting trend; in the large gross pool, terms 'repair', 'refurbish' and 'renovate' are used more frequently than when delimiting with 'circular', whereas terms 'recov' and 'reuse' appear more frequently in the 'circular' delimitation. From the same figure, it is also seen that some of the applied keywords do not seem to appear in the included titles. These keywords were, however, included to assess the mapping in a holistic manner, considering the predecessors of CE. Some of the search string keywords only presented a few contributions in the original pool of search results, which were however sorted out throughout the screening and sorting iterations, before the gross pool, as presented in Figure 3, due to lack of topical conformance.

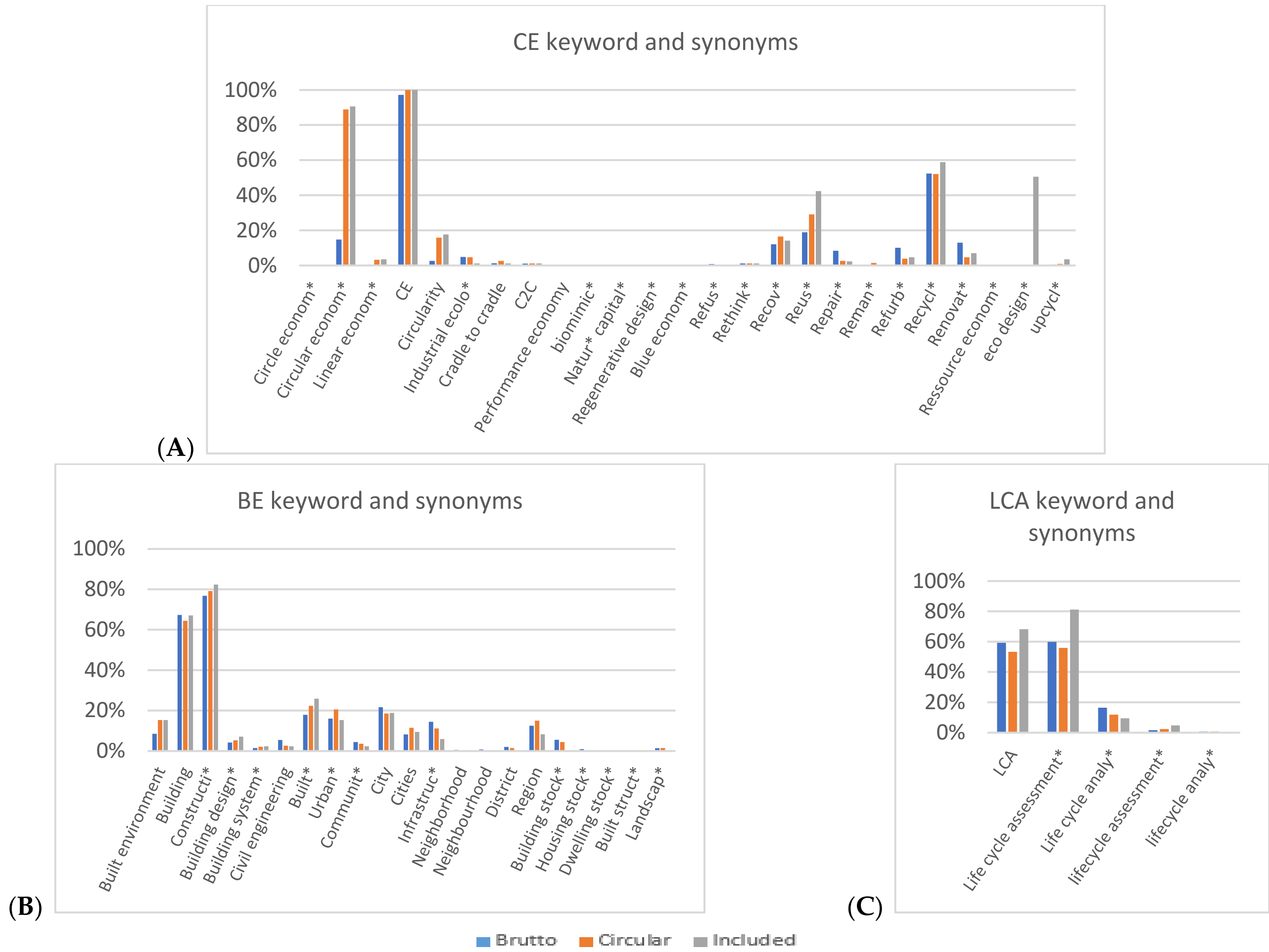



**Figure 5.** Appearance of search keywords/synonyms throughout the literature sorting process. the trends/appearance is shown as a percentage of the total number of papers in the pool, i.e., gross pool: 2046 papers, circular delimitation: 140 papers, final included: 85 papers. (**A**) CE synonyms, (**B**) BE synonyms, (**C**), LCA synonyms/variations. Asterix (*) in the search keywords, indicate the use of the wildcard function in searches.

### 3.4.2. Synthesis of Included Studies

Looking at bibliometric extractions on the included studies, from Figure 6a, it is seen that the relevant papers, applying the term 'circular' in the context of LCA and BE, appear in 2016 ($n$ = 1). In 2019, the number of published article and conference proceedings more than tripled ($n$ = 17), whereas in 2021, the number of relevant published studies was ($n$ = 33). The number of published articles in 2022 was, at the last search performed mid-March 2022, $n$ = 7, but it is to be presumed that the publishing trend from the previous years will also increase in 2022.

Looking further into the publication trends of the included papers, (see Figure 6c,d) it was found that most papers were published as journal articles ($n$ = 71); and a significant number of conference proceedings ($n$ = 14). As the inclusion criteria required the included studies to contain at least one quantitative case study, concluding on whether CE pays off environmentally, three overall categories of study designs were found: Case study papers, method development with case studies for testing, and review papers leading into method development and/or test on case studies. Across both types of publications, it was found that most papers were predominantly case studies ($n$ = 66), followed by methodology papers ($n$ = 18), and the least were based on reviews as their main focus ($n$ = 1).

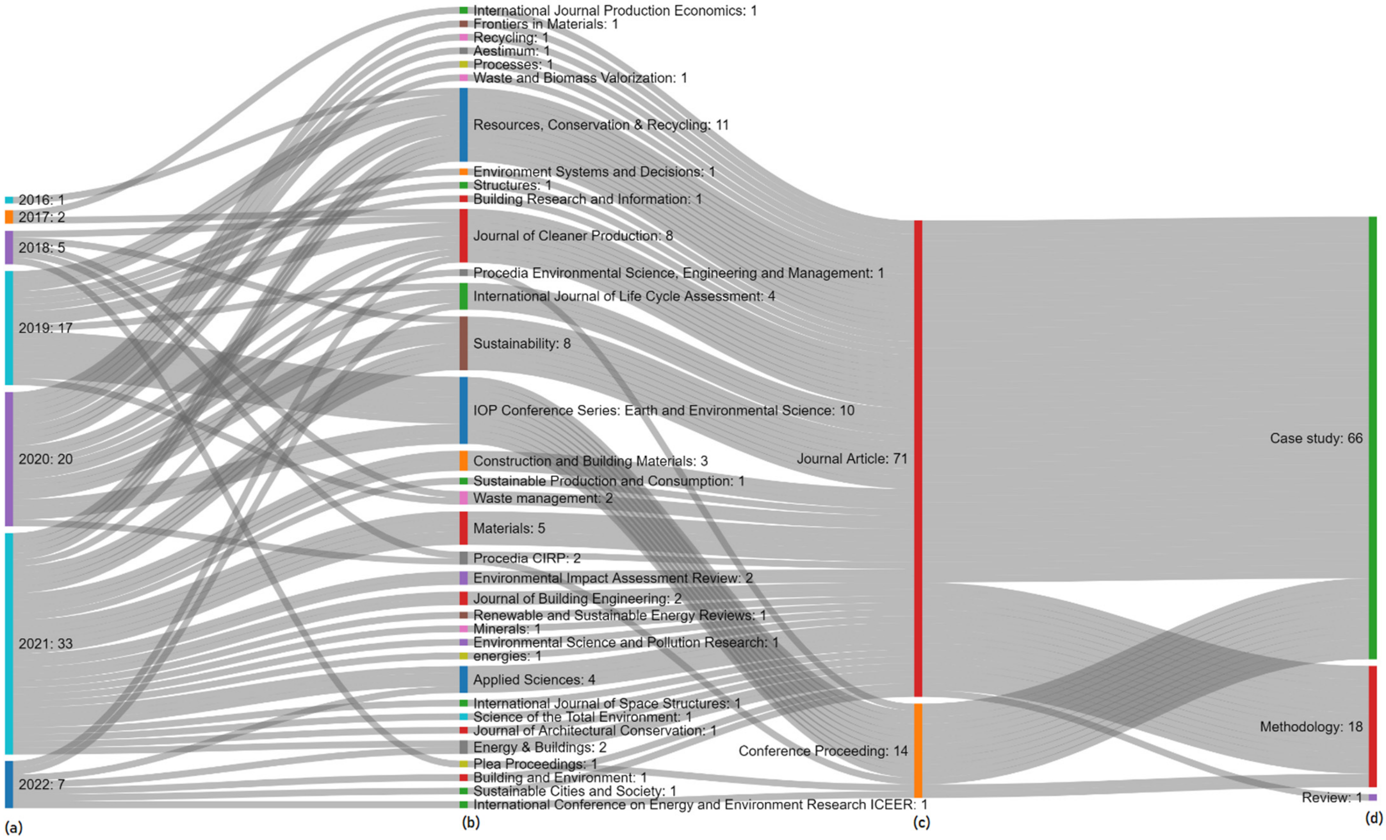



**Figure 6.** (**a**) Temporal trends, year of publication, (**b**) Journal of publication, (**c**) Type of publication, (**d**) Type of paper.

Across the types of publications and papers, the included studies appear in a great variety of journal and proceeding series (see Figure 6b). However, a few stand out as dominant publishers, being Resources, Conservation & Recycling ($n$ = 11), the IOP Conference Series: Earth and Environmental Science ($n$ = 10), and the Journal of Cleaner Production and Sustainability ($n$ = 8).

Looking at spatial trends for the papers, from Figure 7a,b, it is seen that most papers were conducted by main authors with first/main affiliation in Europe ($n$ = 64), where the most represented country is Italy ($n$ = 13) and the second most is Spain ($n$ = 12). Looking at the cases in Figure 7c, most published cases refer to Spain ($n$ = 11). It is also noticeable that not all studies present the geography of the case study ($n$ = 4), and other studies have a wider scope than a single country ($n$ = 1), i.e., [31], who assesses the EU-27. Others assess several locations, either through several cases or through geography sensitive scenarios ($n$ = 6), e.g.., [32] whose cases are located in Denmark and Sweden, [33], whose cases are set in three geographical contexts (Spain, the Netherlands, and Sweden), [34], who collected data from the Netherlands and Spain, and [35], whose case scenarios assess different geographical contexts in India (Chennai), Canada (Vancouver), and South Africa (Durban).

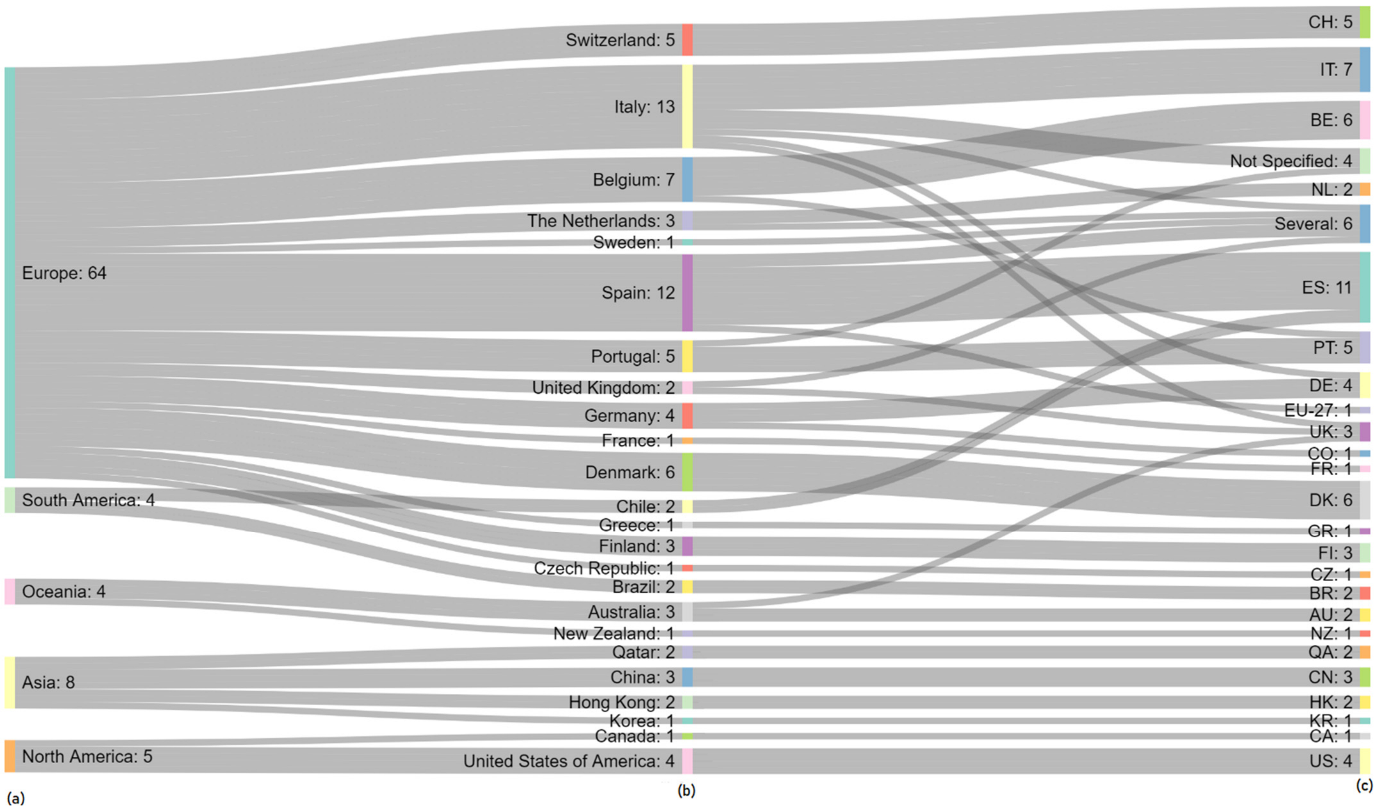



**Figure 7.** Spatial trends, (**a**) Region of the main author, (**b**) Country of the main author, based on first listed affiliation, (**c**) location of case study.

Diving into the content of the papers, Figure 8a, it was found that the scales most predominantly assessed in the case studies were materials ($n$ = 28), followed by components ($n$ = 18), with the least being neighbourhood and/or city, both with ($n$ = 1). The most assessed CE definition, using the R-imperatives as measure, was recycling ($n$ = 36), followed by reuse ($n$ = 32), with the least being not represented at all (refuse, rethink, repair, reduce, remanufacture, and along with 'downcycling) ($n$ = 0) (see Figure 8b.). A number ($n$ = 12) of studies assessed several imperatives, e.g., [32], who assesses case studies applying upcycling and Design for Disassembly (DfD) respectively; [36], whose circular design case applies DfD principles with the options of reuse, recycling, and recovery; [37], who assesses reusable masonry blocks produced from recycled CDW; and [38], whose guidelines are derived from case studies on 'the circular kitchen', assessing various circular value retention processes (VRPs), e.g., a variant designed with recycled contents and one enabling reuse of the single components.

Looking at Figure 8c, it is seen that most studies ($n$ = 53) assess CE solutions up front, using, e.g., recycled waste in new materials or structures [39], recycled concrete in aggregates [40], or reusing cut-offs from the automotive industry, or offal, in new building façade designs [41]. Some ($n$ = 17) assessed prospective CE actions, e.g., through adaptable design and DfD [42–48], and the rest ($n$ = 15) assessed both up front and prospectively, e.g., through cases that both used secondary materials and were designed for recycling or reuse [33,37,49–51].

However, regardless of assessment temporality, most studies conclude that the proposed CE subject will pay off ($n$ = 66) or will pay off overall ($n$ = 4)(see Figure 8d). Examples of the 'yes, overall' could be [52], where the one design proposed outperforms the BAU in 6 of 11 impact indicators but the other proposed design outperforms the BAU in all impact categories, or [53], who concluded that the use of recycled gypsum waste compared to gypsum using natural or FDG was predominantly positive. Some studies ($n$ = 14) were more ambiguous in their conclusion, often due to the fact that the proposed CE solutions showed reductions on some impact categories, but not all, as in, e.g., [23,31,54–56].

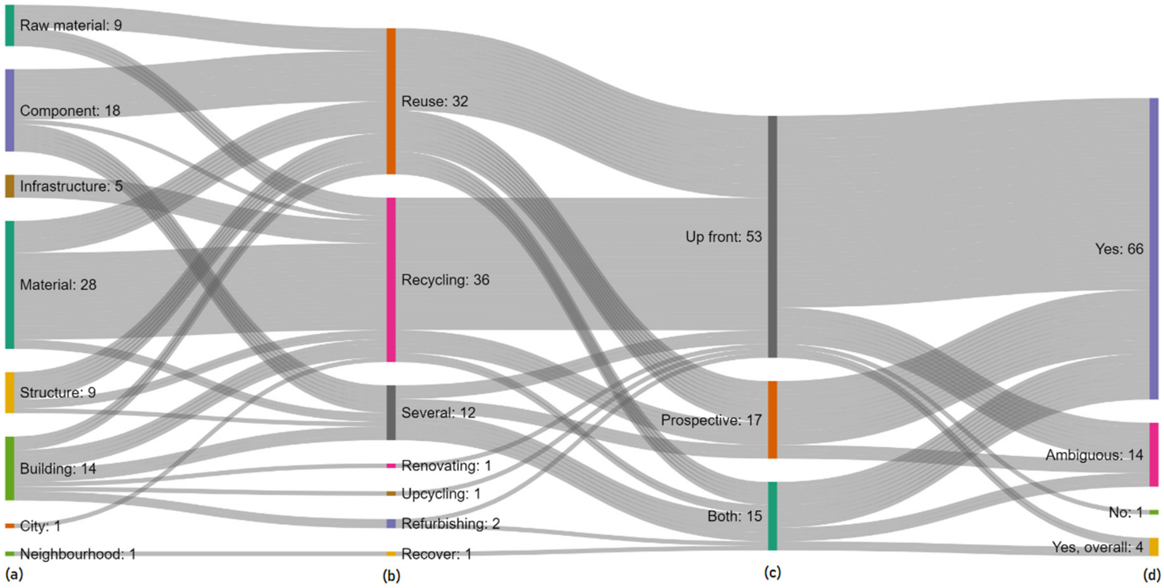



**Figure 8.** (**a**) Scale of study/case/stock, (**b**) Definition of CE, (**c**) CE temporality, (**d**) Does CE pay off, environmentally.

Though the conclusion seems to be streamlined, the measures and methods applied, on which this conclusion is drawn, vary, as shown in the following figures. Considering the applied LCA methodology reference (see Figure 9a) it was found that most papers were referencing the ISO standards for LCA (ISO 14040/44), either as a sole methodological reference ($n$ = 38), in combination with one or both European norms for the BE (EN 15804/EN 15978 and coherent PCR documents, e.g., EN 16757, as in [37]) ($n$ = 6), or in combination with specifying guidelines ($n$ = 5), e.g., Level(s), national guidelines, or the ILCD handbook. Some of the studies only referred to the ISO standards but presented the results of the case studies according to the modularity, as given in the European norm ($n$ = 8 of the 38). A considerable number ($n$ = 19) did not define their reference explicitly (noted as 'inconclusive'). While this categorisation shows how LCA methodological references are addressed, they should be read with some caution, as when using the European Norm as reference (as stated by $n$ = 14), the LCA assessors should also automatically comply with ISO, which is not addressed by the simplification, as it only lists the details specifically given by the authors. In addition, PEF and ILCD was referred to as method ($n$ = 1) respectively, and one ($n$ = 1) paper applied the EN combined with a national guideline [36].

It was found that most papers ($n$ = 61) did not explicitly address whether they applied the attributional or consequential LCA approach. Of the papers stating their approach explicitly, attributional LCA was applied in ($n$ = 19), and very few publications also claimed to apply a consequential approach ($n$ = 5) (see Figure 9b.). Of the large portion not disclosing the applied approach explicitly, some of these could be presumed to apply ALCA through their reference of applying the methodology from EN15804 and/or EN15978.

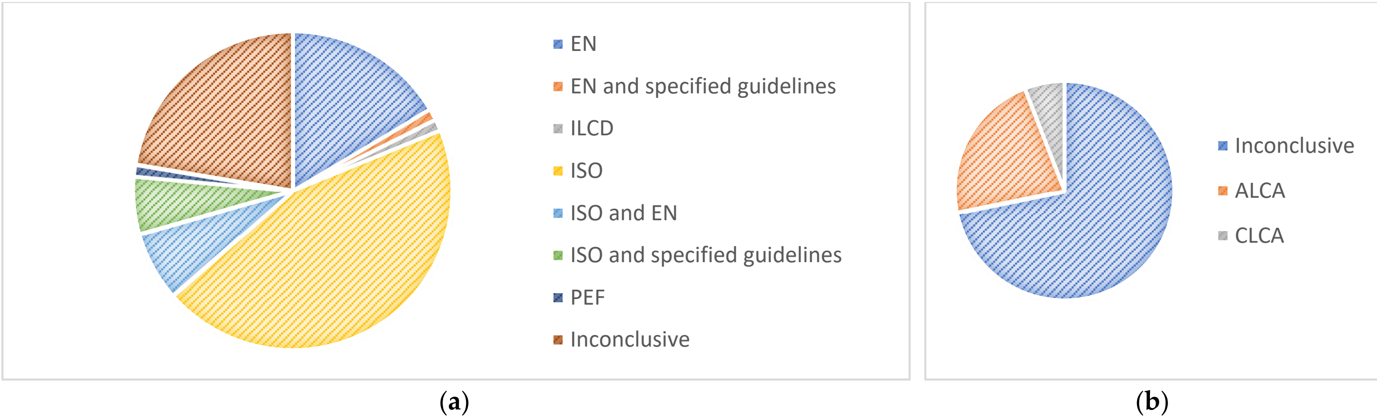
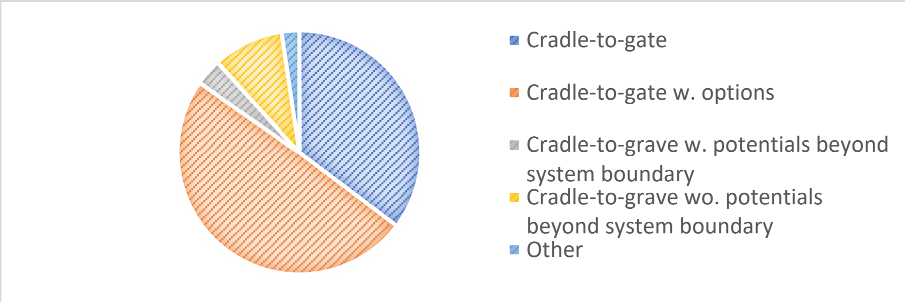


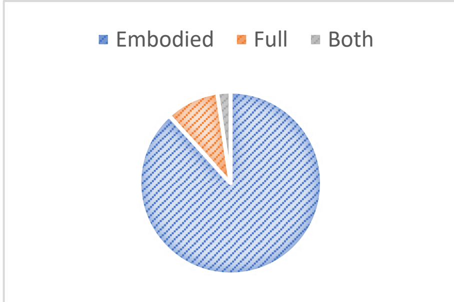

**Figure 9.** (**a**) LCA reference, (**b**) LCA methodology and approach.

Using the system boundary definitions as met in Environmental Product Declarations, according to EN15804:2012 + A1:2013 [2] (Cradle-to-gate, Cradle-to-gate with options, and Cradle-to-grave w./w.o. module D/potential beyond system boundary), we additionally define a category for 'Other', covering studies assessing EoL [57], or Construction, Use and Deconstruction [58]. The assessed system boundaries predominantly represented cradle-to-gate w. options ($n$ = 42), with the second most being cradle-to-gate ($n$ = 30), regardless of whether the studies were conducted according to 'only' the ISO standards, or following the modularity of the European norms for the construction industry, see Figure 10a. The division was simplified, to be represented in the figure; however, the boundary definitions in the case studies were very inconsistent, and the definition 'Cradle-to-gate w. options', contains both studies including production and installation e.g., [59], studies including production, replacement and EoL, e.g., [60,61], and studies including dismantling of refurbishment and production of replacement materials, in, e.g., [62]—being thus very broadly scoped. In contrast, whether the studies assessed embodied or operational impacts, these were easier to define. As seen in Figure 10b, most studies ($n$ = 75) assessed the embodied impacts only, whereas some ($n$ = 8) assessed a 'full' cycle, including both embodied and operational energy. However, a 'full' life cycle does not necessarily entail that all life cycle stages are included, as in, e.g., [63], where the life cycle stages included followed the requirements as applied in the Danish building industry (embodied represented through: A1–A3, B4, C3, C4, D, and operational in B6). A few studies ($n$ = 2) are marked as addressing 'both', which entails the studies having different scopes in different cases, e.g., [64], who perform a case study at building element level (only considering production), and one case study being at building level, including the following life cycle stages (when considering the European Norm): A1–A3, A4–A5, B4, B6, C1–C4, and D.

When performing the studies, both the source of data (foreground and background respectively) and the calculation approach and software vary. Foreground LCI data sources were mentioned as literature, manufacturer data, and experimental data, whereas background databases (see Figure 11) were predominantly found as ecoinvent (various versions) ($n$ = 41), GaBi ($n$ = 4), EPDs ($n$ = 3), and through the tool tools applied, not specified further, e.g., OneClick LCA ($n$ = 2) and Tally® ($n$ = 1). The applied background database was found to be inconclusive for ($n$ = 7), whereas some addressed using multiple databases ($n$ = 19), e.g., [65], using ecoinvent, US EPA, and Eurobitumen, [66], using GaBi and SICV Brazil, and [67], using Chinese Life Cycle Database (CLCD) and the European reference Life Cycle Database (ELCD).




(**a**)




(**b**)

**Figure 10.** (**a**) System boundary, phases, (**b**) System boundary, impacts, defined as embodied impacts, 'full' cycle (including both embodied and operational energy, however not necessarily all life cycle stages), and 'both' (entails the studies have different scopes in different cases, e.g., one considering only embodied, and another considering both embodied and operational impacts, thus 'full').

Various national databases appeared in few cases, e.g., Korean LCI DB ($n$ = 1), Swiss Federal LCA database KBOB ($n$ = 1), and Ökobau ($n$ = 1). While these are noted explicitly used in the assessed papers, and therefore are listed explicitly in this review, the data in these databases may be or are to a great extent based on other databases, e.g., ecoinvent, EPD providers, etc. Some databases or sources were mentioned for singular studies ($n$ = 1), e.g., ELCD, Literature (applied for emission data), PaLATE, SCION, and the World Resources Institute.

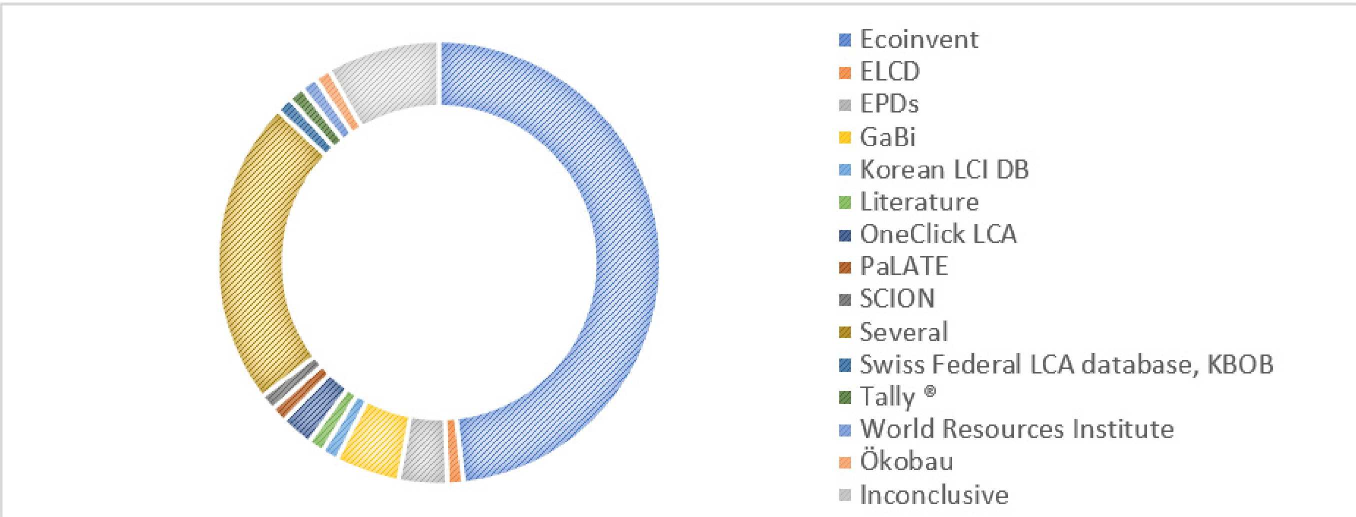



**Figure 11.** Background LCI database.

Once the overview of the LCIs were established, most studies used commercial LCA software SimaPro ($n$ = 28) to model their product system; however, OpenLCA ($n$ = 14) and GaBi ($n$ = 5) were also used (see Figure 12). Additionally, other, more national approaches were used, e.g., LCAbyg from Denmark ($n$ = 2). Moreover, some studies based their calculations on simplistic addition of emissions or other manual calculations ($n$ = 16), and others did not state explicitly how their results were derived ($n$ = 11).

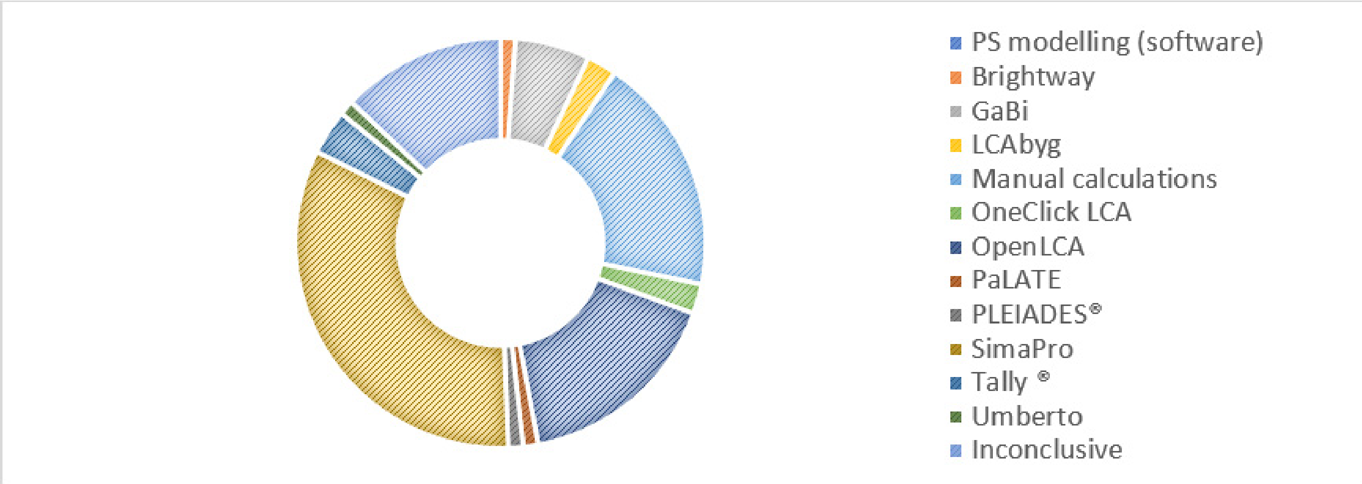



**Figure 12.** Product system modelling 'software'.

Regarding the applied LCIA methodology (see Figure 13), most studies applied CML developed methods (*n* = 22) in some variation, referencing either other studies applying the method or following the EN15804 + A1:2013/EN15978 approach (*n* = 6), i.e., [35,46,54,63,68,69]. Other LCIA methods applied were ReCiPe (*n* = 9), IPCC (*n* = 7), Impact 2002 + (*n* = 5), CED (*n* = 2), and ILCD (*n* = 2). Of the papers using ILCD as an LCIA method, one of them was through EN15804:2013 + A2:2019 [57]). Additionally, various LCIA methods were found to only appear as (*n* = 1), i.e., Chinese National Standard "Building carbon emission calculation standard (GB/T51366-2019)", EuGeos, PaLATE, and TRACI. Some studies did not explicitly state which LCIA method they applied (*n* = 16). Few studies applied several LCIA methods to comprehend potential variations of methods (*n* = 5), e.g., [70], who used two different GWP methods to increase the robustness of the results using GWPbio [71] and the IPCC GWP100. Other examples of this are [72], who applied ReCiPe and Impact 2002 + , [73], who applied three methods (CML, ILCD and ReCiPe) to reduce the level of bias, and [74], who used EF3.0 but supplemented the GWP with IPCC results. Others applied several LCIA methods, including indicators complementary from different LCIA methods (*n* = 13), e.g., [75], applying IPCC and USEtox, [76] applying IPCC, AWARE, CED, and the Product Material Footprint, and [64] applying IPCC, CED, and Swiss Ecopoint.

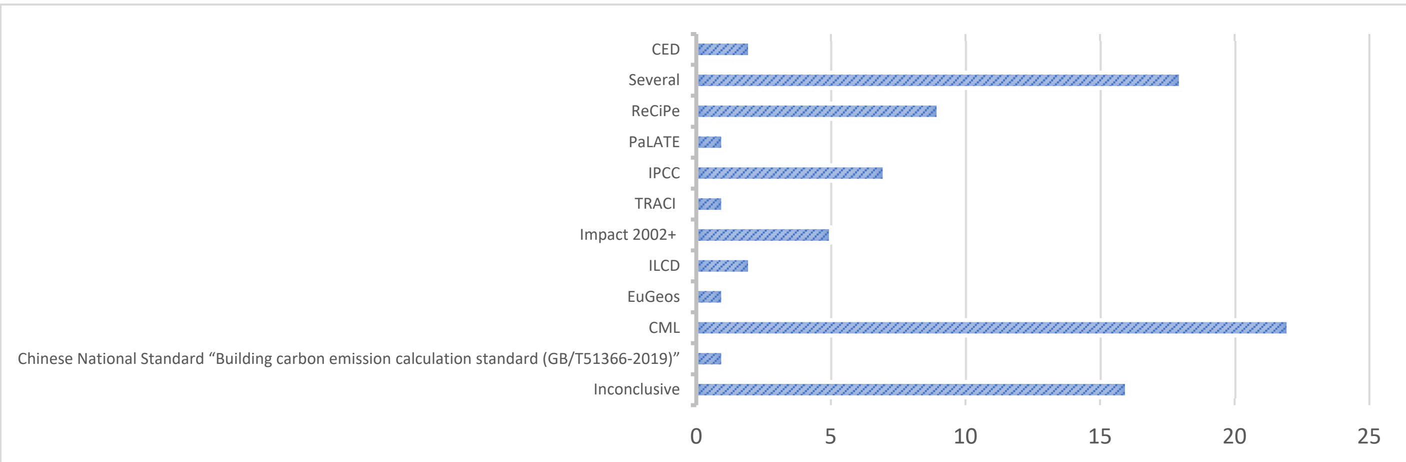



**Figure 13.** LCIA method applied.

While the applied LCIA methods may indicate which impact indicators are obtained, no consistent application pattern was found. A synthesis of the applied indicators in

Figure 14, show that most studies applied only midpoint indicators (*n* = 74), none presented endpoint indicators only (*n* = 0) and some presented single score only (*n* = 4). Other studies presented several steps, showing both midpoint and endpoint (*n* = 4), midpoint and single score (*n* = 2), or all three (midpoint, endpoint, and single score indicators) (*n* = 1).

Looking at the studies applying midpoint indicators (*n* = 81), the studies applied everywhere from 22 midpoint indicators (*n* = 1) to 1 single midpoint indicator (*n* = 22). A similar overview was made for the studies applying only endpoint indicators (*n* = 5), where it was found that the number of endpoint indicators varies from 5 to 1 (*n* = 1). However, these values are not representable to full, as some of them, applying several LCIA methods, are double counted, e.g., [72], where some of the counted midpoint categories are according to ReCiPe, some are for Impact 2002+ , and some of them are only counted once, e.g., GWP in both LCIA methods. Therefore, the used impact categories are aggregated in the following, to get an overview of the 'declared'/assessed impacts.

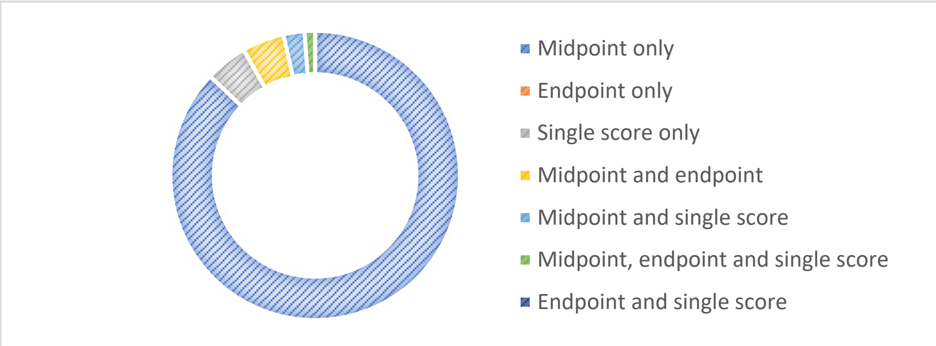



**Figure 14.** Characterisation, normalisation and weighting of results.

Even though LCIA methods are intended to enable the quantification of environmental impact indicators in a streamlined and common language, this was not found to be the case. While some of the differences naturally occur across the LCIA methods (due to the difference in naming, temporal scope, unit indicators, calculation reference etc.), it was also experienced that papers using the same LCIA method would name the indicators differently. Thus, when synthesizing the indicators used, in Figure 15, impact categories at midpoint have been aggregated—e.g., studies assessing global warming potential (GWP), Climate change (CC), Greenhouse Gas emissions (GHGe), $CO_2$ emissions etc., have been synthesized into 'Global Warming', categories considering some sort of land use or transformation have been synthesized into 'land use', categories considering ecotoxicity, e.g., terrestrial ecotoxicity, aquatic ecotoxicity potential, are synthesised into 'ecotoxicity', etc. The midpoint impact category most often represented in the studies was found to be Global warming (*n* = 80), [77] being the only study using midpoint impact categories not addressing Global Warming. This is due to the study using a single score for the results but introducing CML baseline method midpoints (acidification and eutrophication) [77]. The second most applied/addressed impact category is acidification (*n* = 44), followed by resource (*n* = 43) and eutrophication (*n* = 41), while the least was waste streams (*n* = 5). Considering the endpoint indicators, the applied were considering ecosystems, resources, climate change, and human health.

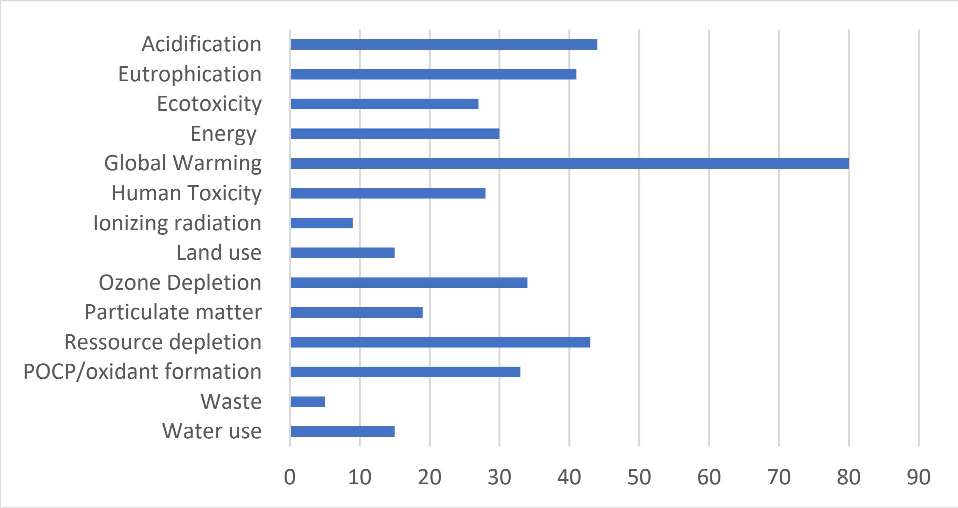



**Figure 15.** Environmental impact, midpoint, indicators used, simplified synthetisation.

Most studies did not assess sensitivity ($n$ = 56), see Figure 16, while the ones that did ($n$ = 29) assessed the sensitivity with various approaches and aims. While some assessed the quantitative values of their input data ($n$ = 15), others assessed e.g., the impact of transportation modelling ($n$ = 6), while some applied purpose developed scenarios and prospective assumptions ($n$ = 14), e.g., by testing the modelled number of cycles or the lifespan assumptions [52,55,56,78] by adding additional scenarios [39,58,61,76,79] or by interchanging the allocation or system boundary limitation [39,70,73,80]; one ($n$ = 1) tested the most suitable solution by varying MCDM weights [65]. Some of the studies tested several sensitivity aspects.

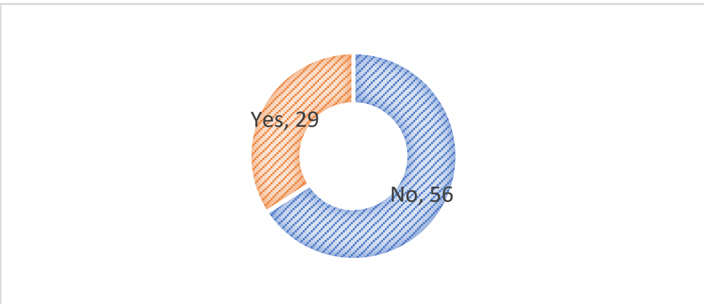



**Figure 16.** Sensitivity analysis inclusion.

## 4. Discussion

### *4.1. Summary of Evidence*

In this scoping review, we identified 85 primary studies presenting some kind of LCA study within the Built Environment and construction industry with an explicitly defined interest and focus on CE. The main question we asked in the study was: 'what are the questions we ask, and how are we seeking to answer them?', when using LCA to assess CE in the BE.

#### 4.1.1. LCA Approach and Decision Making for CE

From the review it appears to be confirmed that the majority of the assessments stick to the classical and simplistic way of performing building LCAs (i.e., ALCA applying the cut-off system model) as prescribed in EN15804 and/or EN15978. While the correlation between building (or material), i.e., micro level, andthe society (i.e., macro level), and the scaling and recommendations done on these may have been somewhat acceptable when considering building principles in a linear economic system, this might change when transgressing into a circular economy, introducing system changes and potential burden shifting across system boundaries and rebound effects. Nonetheless, from the review it is found that most studies still assess CE in the BE, using an attributional approach, concluding that CE pays off environmentally—most often without addressing this choice of approach actively or the EU recommendations regarding the valid decision context associated with the types of LCA [1].

#### 4.1.2. Allocation

When considering applied allocation approaches, a concrete synthesizing was determined to be impossible, as this would need significant simplification and "guesstimations" due to a lack of inconsistent addressing of these topics throughout the included papers. Most studies did not explicitly define what approach was applied, considering the allocation of the system boundaries, i.e., how they handled secondary functions and co-products in the system boundary. However, some studies did explicitly state application of the cut-off approach, also sometimes referred to as the 100:0 allocation, e.g., [43,44,69,81,82], and a few reported explicitly applying system expansion, e.g., [61,74]. Some studies could (only) be presumed to use the cut-off approach as prescribed by EN15804 and EN15978, even though some studies referenced the European norms but explicitly stated that they had applied another allocation approach, e.g., [38,56].

#### 4.1.3. Timing of LCA Application

While the main interest of the review was which questions we are posing when applying LCA in case studies investigating the environmental implications of CE applied to the BE, another finding was the number of studies where LCA was performed relatively thoroughly, this, however, not being the main focus of the case, but merely an add-on. Examples could be [59,83], which both have a main focus on the technical feasibility. It should be kept in mind that the technical feasibility is highly relevant, as the aim of environmental benefits is not achievable if the suggested solution is not technically feasible. However, an open argument appears—in what order should these things be assessed? Should LCA be carried out first, on a theoretical level, before commencing large scale technical physical tests, or should we ensure technical feasibility before assessing potential benefits? These discussions are also reflected in many 'early design phase LCA studies' at present.

#### 4.1.4. Barriers for Learning from Other Industries

CE is discussed in all industries, and for some, the application of LCA (and the approach used) seems more straight forward than what is done in the BE. Thus, an area that should be looked into further is why we tend to stay within a business-as-usual or default application of LCA in the BE, when other industries have changed their methods or have always been using other approaches. Is it because we have the static European Norm (EN), or is there another code we have not cracked yet? Some authors point to the methodology in the EN, which needs development, e.g., being able to handle multiple cycles, or by changing the allocation approach; however, others point to the main approach applied (i.e., ALCA) as being wrong for answering questions regarding CE. Still others point to the significantly longer lifespan in the construction industry, and thereby the prospective uncertainty compared to other industries, as being the main obstacle/difficulty.

Many of these issues are discussed in the literature, through e.g., method development papers (mainly taking their starting point in the current standards though). However, it seems that most studies aim to answer the question of whether or not a proposed CE action 'pays off' by looking at it through a static approach (either upfront reuse or recycling, or by including potential avoided use of materials in the next service life—enabled through e.g., DfD).

Thus, the questions asked are found to align with the questions asked historically in a linear economy without taking into account central issues and risks of e.g., rebound effects or burden shifting across industries or merely different scales in the construction industry—i.e., what consequences does a CE proposition on e.g., a material or building level have on a societal level?

## *4.2. Limitations*

### 4.2.1. Delimitations

While this scoping review identified a significantly larger bulk of studies than originally expected, some limitations in the study appear. A primary limitation, which may skew the mapping of available material, is the narrowed focus on studies that address 'circular' in the paper. It has become predominantly explicit throughout the sorting and selection process that many studies may address circularity through imperatives such as 'reuse', 'recycling' etc, without defining it as 'circularity' specifically. An example of this, though included, is Zhang et al. (2018), who only use the term 'circular' in the abstract. This placed the study in the pool of papers to be reviewed; however, throughout the rest of the paper, they address the imperative recycling as a beneficial strategy to obtain climate mitigations [84].

Thus, if the scope of the study was extended, some of the findings in this scoping review might vary. However, the focus of this study was applied to address those papers that specifically state their aim to assess the environmental impacts or benefits of introducing circular mass flow action(s) in the design or processes within the construction industry. In future work, one may apply several, more narrow reviews on how LCA is applied on e.g., the question on 'reuse', 'recycling', 'upcycling', 'renovating' etc, within the construction industry, without using the delimiter 'circular' but focusing on how LCA is interpreted and applied.

Considering another delimiter applied, namely the need for the study to address 'LCA' instead of the broader 'environmental assessment', some studies containing assessments of e.g., the embodied impacts, did not define the analysis as a 'life cycle assessment'—even though other studies use this definition, though only performing a cradle-to-gate assessment. Examples of this could be Zaman et al. (2018) [85], who explicitly claim to not perform an LCA, and thus were excluded from the pool of evidence, although they assess the environmental benefit of embodied impacts by substitution of virgin materials by harvested materials from a demolished/deconstructed building. Another example could be Brütting et al. (2019) [83], which is included, assessing the reuse of structural steel components; however, the applied assumptions of the LCA are based on and refer to a previous study by the same authors [86], which was not included in the search results due to 'LCA' not being present in the title, abstract, or keywords. The delimitor may raise a more general discussion on the use (correct or incorrect) of the term LCA and what such a study should include. This is however not covered in this review.

### 4.2.2. Inclusions and Scale

Another limitation appearing in the assessment or scoping may be found in the initial sorting of the extracted bulk literature from WoS and Scopus. The sorting was performed on titles and keywords, omitting, amongst other, systemsof urban scale and domestic consumption. However, when discussing CE on a larger scale (being this urban, city, region, country, or global), this is often done by considering flows (e.g., water, waste, energy), and the terminology used is often metabolism. Thus, this limitation consists of the following consideration: does the review at hand omit the macro level of society and thus how environmental implications are applied (i.e., often through material flow analyses, MFA, Multi Regional Input-Output analysis, MRIO, and extended environmental impact-output analyses, EEIO)?. As found by e.g., Petit-Boix and Leipold (2018) [87], a key strategy for CE in cities, and one which is studied by academia, is waste management. Petit-Boix and Leipold (2018) assessed literature using industrial ecology tools, covering LCA, MFA, input-output, and carbon footprint [87].

However, as seen from the coherent review, numerous studies apply design solutions within the scope of the circular economy of material, buildings, neighbourhoods etc, assessing the environmental implication and concluding that CE pays of without considering the larger picture that the product, building etc. plays into. Thus, while the review might overlook the assessments at a greater scale, it underlines the lack of studies considering CE at micro level and consequences on macro level, as also pinpointed by [29].

#### 4.2.3. Exclusion Criteria

In order to present the current state of the research, the scope of the final pool of literature was limited to papers presenting at least 1 quantitative case, which omitted some studies; additionally, the case must be concluded on whether CE actions pay off. Many papers touch upon the exact question of how LCA should be applied considering CE in the BE, e.g., in methodology papers. An example, excluded due to the latter criteria, is Eberhardt et al. (2020) [88,89], by the same authors, and De Wolf et al. (2020) [90], who respectively developed and assessed LCA allocation approaches for CE in the BE and tested it on a case study, which did, however, not conclude on whether CE pays off, but concluded regarding which allocation approach incentivizes which R-imperative/CE action.

## 5. Conclusions

The review presented a mapping of the questions asked regarding the environmental performance (assessed through LCA) of building principles and CE. It demonstrates that the lack of applicable and adequate methodology when introducing CE prompts the development of 'new' methodologies, often a spin-off or extension from either the European norm for construction or another ALCA approach.

From the review, it is found that the questions asked regarding LCA of CE in the BE do not change significantly from business-as-usual questions asked in the linear economy. Some studies are questioning the methods (mainly taking their starting point in the current standards though). However, it seems that most studies aim to answer the question of whether or not a proposed CE action 'pays off' by looking at it through a static approach (either upfront reuse or recycling or by including potential avoided use of materials in the next service life—enabled through e.g., DfD).

The conclusion on whether a CE proposition pays off or not is also based on a single indicator, e.g., impact category—most often considering climate change. And while climate change is of great importance, the agenda around CE should be acknowledged for being a means for mitigating other challenges as well, irrespective of whether they are urgent or prospective challenges.

The complexity of the answers looked for when discussing CE inherently introduces new questions, which we are currently not addressing in the literature. It introduces subjects of e.g., rebound effects or burden shifting across industries, but also increases the complexities of the questions we ask. The potential benefits of DfD in a temporal scope of 100-200 years cannot be answered by the same 'answer' as the reuse of a single product up front. Thus, the questions we ask need reiteration and adjustment.

**Supplementary Materials:** The following supporting information can be downloaded at: www.mdpi.com/article/10.3390/su14116887/s1, Table S1: Case study characteristics; Table S2: LCA characteristics.

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## Appendix A

*Peer-Reviewed Literature*

Besides the keywords, a couple of basic search criteria are applied to every string in the two databases.

Web of Science

- Database: Web of Science Core Collection, editions; all
- Document types: Articles, proceedings papers, review articles, early access, corrections/additions
- Language: English, Danish or German
- Date range: publication date; 1900–2021
- 'Topic' field tag

Scopus

- Search within: Article title, Abstract, Keywords
- Timespan: All years (1960–2021)
- 'Topic' field tag represented by 'Article title, Abstract, Keywords'
- Added to Scopus: Anytime
- Language: limit to English, German, Danish
- Document types: Articles, conference papers, review, erratum

## Appendix B

**Table A1.** Qualitative paper characteristics.

| Authors | Ref. | Type of Study | Scale of Case | CE Proposal/Object of Case Study | CE Concept Studied |
|---|---|---|---|---|---|
| (Bonoli et al., 2020) | [91] | Case study | Material | Asphalt concretes from RAP aggregates and steel slag | Recycling |
| (van Stijn et al., 2021) | [52] | Methodology | Component | Kitchen modules | Several |
| (Wiprachtiger et al., 2020) | [75] | Methodology | Material | Thermal insulation in residential buildings | Recycling |
| (Romnée et al., 2019) | [78] | Case study | Structure | Greenhouse structures | Reuse |
| (Sanchez et al., 2019) | [92] | Methodology | Structure | Adaptive reuse design of building | Reuse |
| (Sandanayake et al., 2022) | [93] | Methodology | Raw material | Soil-waste based geopolymer cements | Reuse |
| (Russo et al., 2021) | [65] | Methodology | Infrastructure | Road asphalt Pavements using waste as raw material | Recycling |
| (Meek et al., 2021) | [39] | Case study | Component | Stabilised rammed earth using recycled waste and industrial by-products | Recycling |
| (Lopez-Garcia et al., 2021) | [94] | Case study | Material | Ceramic bricks, using olive pomace | Reuse |
| (Toniolo et al., 2021) | [51] | Case study | Structure | Temporary exhibition installation, applying DfD | Reuse |

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|---|---|---|---|---|---|
| (Vandewalle et al., 2020) | [81] | Case study | Infrastructure | Pavements, using multi-recycled RAP mixtures | Recycling |
| (Caneda-martínez et al., 2021) | [95] | Case study | Raw material | Cement pastes, using recycled concrete powder and CDW | Recycling |
| (Caldas et al., 2021) | [70] | Case study | Material | Bio concrete, using wood waste | Recycling |
| (Vitale et al., 2021) | [96] | Case study | Material | Cement, using CFRP waste | Recycling |
| (Nussholz et al., 2019) | [32] | Case study | Material | Three different materials (and business models) using secondary materials | Several |
| (Al-Hamrani, Kim et al., 2021) | [97] | Case study | Structure | Under-raft foundation using concrete and excavated boulders | Recycling |
| (Silva et al., 2021) | [66] | Case study | Material | Particle boards with recycled wood and biopolymer | Recycling |
| (Mostert et al., 2021) | [76] | Case study | Building | Concrete, using recycled aggregates | Recycling |
| (Zhang et al., 2018) | [84] | Case Study | City | Urban concrete recycling | Recycling |
| (Saadé et al., 2022) | [58] | Methodology | Neighbourhood | Urban develop of neighbourhood blocks, applying different CE approaches, up front and EoL | Recover |
| (Colangelo et al., 2020) | [23] | Case study | Material | Concrete, using recycled aggregates | Recycling |
| (Rodrigo-Bravo et al., 2022) | [68] | Case study | Material | Gypsum ceiling tile, using PU foam waste | Recycling |
| (Uceda-Rodríguez et al., 2022) | [98] | Case study | Raw material | Lightweight aggregates made from waste | Recycling |
| (Lozano-Miralles et al., 2018) | [72] | Case study | Material | Clay bricks mixed with organic waste | Reuse |
| (Eberhardt et al., 2019) | [43] | Case study | Component | Building components: a concrete column, a window and roof felt, applying EoL potentials | Reuse |
| (Nasir et al., 2017) | [99] | Case study | Material | Insulation material using recycled textiles | Recycling |
| (Tsioka and Voudrias, 2020) | [77] | Case study | Material | Alternative management methods of phosphogypsum | Reuse |
| (Diaz-Piloneta et al., 2021) | [100] | Case study | Infrastructure | Aggregates for road construction using steel slag | Recycling |
| (Buyle et al., 2019) | [42] | Case study | Component | Wall assemblies, applying DfD | Several |
| (Liikanen et al., 2019) | [101] | Case study | Raw material | Wood polymer composites, using CDW | Reuse |
| (van Stijn et al., 2020) | [38] | Methodology | Component | Kitchen modules applying reuse and DfD | Several |
| (Brütting et al., 2019) | [83] | Methodology | Component | Steel truss structures, using reused elements | Reuse |
| (Hossain et al., 2021) | [67] | Case study | Material | Partition wall blocks, using waste materials and SCM | Several |
| (Terrones-Saeta et al., 2021) | [102] | Case study | Raw material | Aggregates using electric arc furnace slag | Reuse |
| (Joensuu et al., 2022) | [45] | Methodology | Building | Building structural solutions, applying DfD | Reuse |
| (Di Maria et al., 2018) | [103] | Case study | Raw material | CDW management routes, but assessed through the functional unit of supply of an equal amount of fine aggregates for road construction + coarse aggregates for concrete production | Recycling |
| (Eberhardt et al., 2019 | [44] | Case study | Component | Concrete column applying DfD | Reuse |
| (Wang et al., 2017) | [104] | Case study | Infrastructure | Concrete using recycled aggregates | Recycling |
| (Zhang et al., 2021) | [33] | Case study | Component | Prefabricated concrete element using CDW | Several |
| (Dias et al., 2021) | [40] | Review | Raw material | Recycled course aggregates | Recycling |
| (Cuenca-Moyano et al., 2019) | [105] | Case study | Material | Masonry mortars using recycled aggregates | Recycling |
| (Kakkos et al., 2019) | [64] | Case study | Structure | Internal wall applying DfD | Reuse |

| | | | | | |
|---|---|---|---|---|---|
| (Brambilla et al., 2019) | [46] | Case study | Component | Demountable composite floor system | Reuse |
| (Eberhardt et al., 2021) | [56] | Methodology | Structure | Tunnel structure applying different circular visions | Several |
| (Weimann et al., 2021) | [53] | Case study | Material | Plasterboard waste recycling into plasterboards | Recycling |
| (Antunes et al., 2021) | [57] | Methodology | Building | Building rehabilitation and precast wall system, assessing reuse and recycling at EoL | Recycling |
| (Ma et al., 2021) | [62] | Case study | Building | Building refurbishment project, waste management options | Refurbishing |
| (Gravagnuolo et al., 2020) | [60] | Case study | Building | Historic building conservation | Refurbishing |
| (Suarez-Macias et al., 2021) | [106] | Case study | Raw material | Filler in bituminous mixtures, using biomass bottom ash | Reuse |
| (Minunno et al., 2020) | [50] | Case study | Building | Building design applying DfD | Reuse |
| (Kim & Kim, 2020) | [107] | Methodology | Structure | Noise barrier structure using reused steel beams | Reuse |
| (Kucukvar et al., 2021) | [108] | Case study | Building | Container stadium design construction, reusable | Recycling |
| (Kio & Ali, 2021) | [41] | Case study | Material | Wall system, using waste sheet metal | Reuse |
| (Hossain & Ng, 2019) | [109] | Methodology | Material | CDW of building renovation | Recycling |
| (Monteiro and Soares, 2022) | [47] | Case study | Building | Building design, suggesting EoL potentials | Recycling |
| (Cascione et al., 2022) | [49] | Case study | Component | Wall panels using agricultural waste materials and DfD | Reuse |
| (Peceno et al., 2020) | [79] | Case study | Structure | Noise barrier, using recycled seashell waste | Recycling |
| (Zimmermann et al., 2020) | [63] | Methodology | Building | Building refurbishment | Renovating |
| (Zanni et al., 2018) | [82] | Case study | Material | Concrete using CDW recycled aggregates | Recycling |
| (Eberhardt et al., 2019c) | [110] | Methodology | Building | Building design applying DfD | Reuse |
| (Rivero et al., 2016) | [31] | Case study | Material | Gypsum plasterboard recycling | Recycling |
| (Rajagopalan et al., 2021) | [111] | Methodology | Component | Wall partitioning systems using different CE actions | Reuse |
| (Ghisellini et al., 2021) | [80] | Case study | Material | Concretes using CDW and hemp by-products as aggregates | Recycling |
| (Niu et al., 2021) | [73] | Case study | Component | Structural timber cascading | Reuse |
| (Finch and Marriage, 2018) | [48] | Case study | Component | Light timber frame applying DfD | Reuse |
| (Marconi et al., 2020) | [112] | Case study | Material | Insulation panels reusing leather scraps | Reuse |
| (Rios et al., 2019) | [55] | Case study | Component | Reusable external wall framing | Reuse |
| (Brütting et al., 2021) | [59] | Methodology | Structure | Steel truss structures, using reused elements | Reuse |
| (Peceno et al., 2021) | [113] | Case study | Material | Fireproofing panels using seashell waste | Recycling |
| (Buyle et al., 2019b) | [61] | Case study | Component | Wall assemblies, applying DfD | Several |
| (Simoes et al., 2021) | [114] | Case study | Raw material | Concrete using waste from the pulp and paper industry | Reuse |
| (Cassiani et al., 2021) | [115] | Case study | Material | Concrete using recycled aggregates and SCM | Recycling |
| (Pešta et al., 2020) | [37] | Case study | Component | Masonry using recycled aggregates | Several |
| (Ferriss, 2021) | [116] | Case study | Building | Reuse of post-war architecture | Several |
| (Ali et al., 2020) | [117] | Methodology | Component | Building facades using sheet metal waste | Reuse |
| (Ramos et al., 2021) | [118] | Case study | Material | Particleboards, using corn cob waste | Reuse |
| (Aversa et al., 2019) | [54] | Case Study | Material | Non-loadbearing walls using hemp shives, an agricultural by-product | Reuse |
| (Kakkos et al., 2020) | [36] | Case study | Building | Building design and materials, applying DfD | Several |

| | | | | | |
|---|---|---|---|---|---|
| (Moreno-Juez et al., 2020) | [34] | Case study | Material | Cement using EoL concrete waste | Recycling |
| (Rasmussen et al., 2019) | [69] | Case study | Building | Building design using upcycled materials or DfD principles | Several |
| (Bertolini & Guardigli, 2020) | [35] | Case study | Building | Building components from upcycled shipping containers | Upcycling |
| (Mostert et al., 2020) | [119] | Case study | Material | Concrete using recycled aggregates | Recycling |
| (Zhao et al., 2020) | [120] | Case study | Material | Precast concrete building blocks using recycled aggregates | Recycling |
| (Capuano et al., 2020) | [121] | Case study | Infrastructure | Road pavements, using recycled plastics | Recycling |
| (Quintana-Gallardo et al., 2021) | [74] | Case study | Component | Building façade panel using rice straw | Reuse |

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