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Review

Systematic Mapping of Circular Economy in Structural Engineering

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Abstract: Facing increasing sustainability demands, the construction industry is at a turning point where the implementation of circular economy (CE) strategies plays an essential role in driving the necessary transformation aimed at reducing the environmental impact. To facilitate this shift, structural engineering must effectively integrate circular principles into building design. With the exponential growth of research articles within this field, it is crucial to map the evolution of the research area. The objective of this study is to detail the trends with, challenges to, and research contributions, integration, and material applications of CE principles within structural engineering. Consequently, a systematic mapping of the CE within the field of structural engineering has been conducted in this study. Initially, the mapping process began with the identification of relevant keywords, followed by searches across four databases. Each resulting article was carefully screened against content criteria, culminating in 91 publications that were thoroughly evaluated. The publications were then categorized and analyzed based on attributes such as research type, circular design, materials, and applications. The results are presented through informative figures and tables. The analysis of the research indicates a predominant focus on technical solutions for structural systems, with demountable connections designed to facilitate the future reuse of materials representing more than half of the literature reviewed. A significant portion of the literature also addresses designing from reclaimed elements; these articles reflect a transformation in engineering approaches, incorporating computational design and innovative methodologies. The focus on steel as a structural material is prominent in the reviewed literature. However, there is an increasing focus on timber, which signals a definitive shift toward sustainable structural systems. Recurring challenges identified in the literature regarding the transition to a circular economy (CE) in the construction industry include the need for industry-wide adoption, precise standardization, the integration of digital tools, and the overcoming of related obstacles in policy and market acceptances. Furthermore, the literature demonstrates a significant research gap: the absence of a comprehensive digital framework enabling an effective digital circular structural design workflow.

Keywords: circular economy; sustainable buildings; design for disassembly; reuse; structural engineering; systematic mapping

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1. Introduction

1.1. Motivation

The construction industry is faced with the need to adopt sustainable practices due to increasing material costs, environmental concerns, and the demand for greater efficiency and automation [1,2]. Historically, the construction sector has significantly contributed to global carbon emissions, with the buildings' construction alone being responsible for approximately 40% of global greenhouse gas (GHG) emissions [1]. Recent initiatives, such as the European Green Deal, have established ambitious objectives for net-zero GHG emissions by the year 2050 [3]. This commitment has been a driving force behind the development of the new Circular Economy Action Plan, introduced in March 2020 [4]. This strategy aims to integrate the principles of circularity across the entire life cycle of buildings and encompasses policies that govern construction management, waste and demolition practices, resource utilization, transportation, accessibility, and digitalization.

The new approaches to material use in architectural design following an adaption to CE provide structural engineers with new challenges when ensuring the structural integrity and constructability of new buildings. It is essential to incorporate existing materials and components into the design of new buildings to substantially reduce construction and demolition waste. Advancements in CE principles within structural engineering are crucial for devising improved methods to design structures with limited resources. Therefore, within the circular transformation of the building industry, innovative structural engineering plays a critical role, tasked with the dual challenge of creating structures that are not only adaptable and enduring but also designed with the aim of future deconstruction and reuse.

However, incorporating a CE and resource efficiency into a building design is not straightforward. Designers encounter various trade-offs: the need for structural stability versus the ease of disassembly for future reuse, the durability of the building versus the need for adaptability, and the decision between using simple materials or more complex composites. There is also the consideration of renovating existing structures against the construction of new, improved structures [5].

Currently, conventional building design relies on linear design methods where new materials are selected as design decisions are made; a shift toward integrating CE principles into the design process requires significant changes to this traditional approach. The innovation potential is vast, with global technological developments paving the way for new, efficient methods and solutions. These digital and technological advances are essential for creating new, sustainable methods that meet the demands of resource efficiency [6].

Incorporating CE principles into design processes, a set of 'R-strategies' [7] is often used. Van Buren et al. describe these strategies as the '9Rs', which include refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover, presented in a hierarchical order of circularity [8]. An increased 'circularity' implies the reduced consumption of natural resources and a diminished environmental impact [9]. Given the construction industry's reliance on material supply, these strategies—specifically reuse (product reuse) [8], remanufacture (creating new products from parts of old products) [8], and recycle (the processing and reuse of materials) [8]—are particularly relevant in the context of building design. Evaluating these strategies in the context of structural engineering, Butting and Fivet argue that reuse is the preferable strategy for achieving the most sustainable circular building design [10]. Thus, in the hierarchy of CE strategies relevant to material supply, reuse is the most effective approach at retaining value, surpassing remanufacture and recycling by minimizing the need for physical and chemical alterations [9].

The shift toward a CE in the construction industry requires collaboration among many stakeholders and interdisciplinary work. However, it also requires a deep understanding of what is required within each discipline involved. Therefore, this study provides a detailed systematic mapping of the CE in the field of structural engineering, focusing on how strategies for the reuse of load-bearing material can be integrated into the structural design process of buildings. It highlights current practices, identifies challenges, and compiles a significant database of scientific articles on the topic.

1.2. Definitions

Considering the diverse and wide range of terms associated with CEs and the interdisciplinary nature of the construction industry, this section aims to clarify crucial definitions of terms relating to the topic, which are as follows:

Circular economy (CE). An economy where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised [5].

Deconstruction. A process in which the material's quality, potential for future reuse, and economic value is increased during the conversion process [5].

Design for deconstruction. Approach to the design of a product or structure that facilitates deconstruction at the end of its useful life in such a way that its components and parts can be reused, recycled, recovered for further economic use, or, in some other way, diverted from the waste stream [5].

Design for disassembly. Approach to the design of a product or constructed asset that facilitates disassembly at the end of its useful life in a way that enables its components and parts to be reused, recycled, recovered for energy, or, in some other way, diverted from the waste stream [11].

Structural Engineering. In this paper, structural engineering is defined as a branch of civil engineering concerned with the design, analysis, and construction of structures capable of withstanding the forces and loads to which they may be subjected.

Re-use. The use of products or components more than once for the same or other purposes without reprocessing. Note to entry: reprocessing does not include preparation for reuse, such as the removal of connectors, cleaning, trimming, stripping of coatings, packaging, etc. [11].

Upcycling. A process in which the material's quality, potential for future reuse, and economic value are increased during the conversion process [5].

In the subsequent part of this paper, the acronym 'DfD' will be used to refer to both 'design for disassembly' and 'design for deconstruction', encapsulating the essence of the definitions provided. Moreover, the term 'reuse' will be used in alignment with 're-use' outlined in this section, with 'reclaim' carrying the same implication.

In addition to the more general definitions provided here, the terms specifically tailored to the mapping in this study are explained in Section 3.

1.3. Research Questions

If the CE is to become a common practice in building design, methods for achieving this must be integrated into the workflow of the structural engineer. The objective of this study is to investigate how principles of reuse can be implemented within the structural engineering practice. It aims to outline the current state of the research, key developments, and trends in this field. Thus, the following research questions are formulated:

- What type of research is conducted on structural material reuse?
- What specific CE strategies within structural engineering are developed to promote material reuse?
- What research contributions are observed in the implementation of reuse in structural design?
- What materials and parts of the building structure are most prominently focused on in this research?

The following sections will further detail the research objectives associated with the mapping process. Initially, the research methodology is introduced in Section 2, followed by an explanation of the mapping scheme in Section 3, which is utilized to categorize the findings. Subsequently, the results are presented and analyzed in Section 4. The study concludes with Section 5, summarizing the key findings and drawing final conclusions.

2. Methodology

The systematic mapping methodology aims to organize relevant literature by systematically obtaining references from online databases according to predefined inclusion criteria. The systematic mapping approach, with its rigorous methodology, differs from traditional literature reviews by providing a clear and broad overview of the research field compared with the more specific, in-depth analysis and discussion in traditional reviews. The broad overview is a result of chosen attributes, their given definitions, and the organization and analysis of the literature within these attributes. The presented study is inspired by the work and guidelines of Petersen et al. [12] and Haakonsen et al., who applied the methodology within the fields of structural engineering and architecture [13]. The process starts by developing a predefined search query with carefully selected keywords relevant to the research topic. This query facilitates a search across various online databases, looking at the keywords, abstracts, and titles of research papers. Additionally, specific qualitative and quantitative criteria have been established for the data to be collected, as detailed in Section 2.2. The initial collection from the chosen databases undergoes a thorough screening to remove studies not aligned with the research focus. Subsequently, a detailed review of the relevant papers is conducted, including a snowballing technique [14], which adds significant studies referenced in the screened papers but not found in the initial search. This process is illustrated in Figure 1.

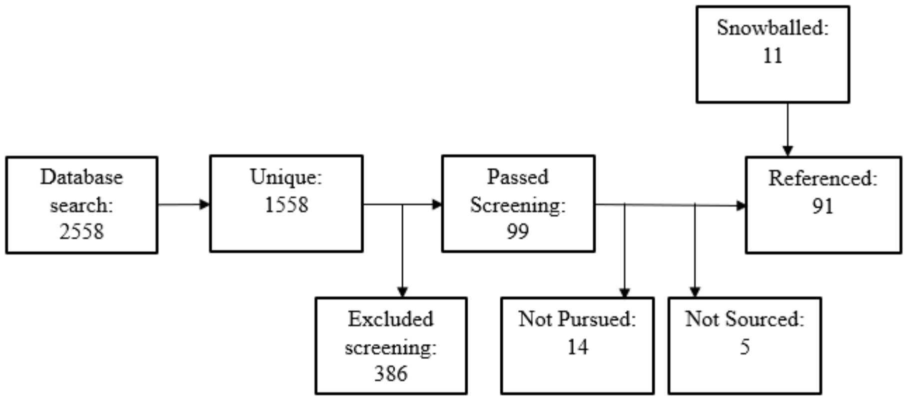


Figure 1. Flowchart representing the mapping process from start to finish, showing the number of publications at each stage.

Upon finalizing the selection of papers that reflect the research conducted in the field, each paper is subjected to a detailed analysis. This analysis applies mapping attributes based on the content, classification, and organization of the papers. The result is a systematic overview of the research on the topic which maps out the thematic breadth, identifies trends in the literature, and highlights research gaps.

2.1. Databases and Search Query

The final search was conducted on 21 December 2023 across the following online databases: Scopus, Oria/NTNU, Web of Science, and Engineering Village. Table 1 displays the number of articles from each database. The same search query, described in Table 2, was used in all databases with only differences in technical formalities. When executing the search query in the databases, Boolean operators 'AND', 'OR', and 'NOT' are used to connect the keywords appropriately. In Table 2, columns are connected using 'AND', except for 'Without', which uses 'NOT', while elements within each column are linked with 'OR'. The keywords in the 'What' column aim to capture elements of building design, 'Where' specifies their application to structural parts, 'How' highlights design through the use of circular economy principles, and 'Without' intentionally excludes specific topics.

Table 1. Publication count sourced from given databases using the search query from Table 2.

Database	Count
Scopus	742
Engineering Village	699
Web of Science	684
Oria	433

Table 2. Search query keywords.

What	Where	How	Without
Structural design	Structural	Circular economy	Fire
Structural system	Building element	Reuse	Aggregat
Building design	Building component	Circularity	
Architectural design	Structure	Reclaim	
		Circular design	

Below is a simplified representation of the search query, without specific formalities. The wildcard '*' denotes variations in forms for the specified word. In situations involving two words, the use of quotation marks indicates the exact word choice without variations; where it is not necessary for the words to appear together in the exact form, 'AND' is added between them:

> ('structural design' OR 'structural system' OR 'architectural design' OR (building AND design)) AND (structural OR structure OR 'building element' OR 'building component') AND ('circular economy' OR reuse* OR circularity OR reclaim* OR 'circular design') AND) NOT (aggregat* OR fire*)

This choice and combination of keywords was the result of a thorough iterative process. The process involved evaluating literature relevance through multiple rounds of varying keywords and combinations to ensure the selection of the most appropriate final search query.

2.2. Screening

In addition to defining the appropriate combination of keywords, the following quantitative criteria for the publications were used:

- Written in English.
- Published in peer-reviewed journals.
- Published within the last 20 years (2003 or later).
- Full text available online.

The papers under consideration for the screening stage were further reduced by following qualitative criteria:

- Abstract must show relevance to structural engineering and the integration of CE principles.
- Abstracts should specifically focus on building design, omitting wider-built environment subjects such as urban planning or transportation.
- Exclude research from disciplines irrelevant to structural engineering.

2.3. Verification

After screening, a total of 80 publications were selected for further analysis, and additional relevant publications were identified using the snowballing technique, resulting in 11 articles [15–25]. Following a secondary snowballing process for the newly included publications, no additional relevant articles were found. As a result, the final collection comprised 91 publications for comprehensive mapping and analysis.

In systematic mapping studies, the quality of collected publications relies on the accuracy of the search query. Therefore, it is essential to verify whether the search query accurately captures the relevant literature. An example illustrating this importance is the inclusion of publications on *DfD* through the snowballing technique [15,17,19,21,23–25], which highlighted the absence of *DfD* as a keyword in the query—a critical aspect initially overlooked. However, the secondary snowballing did not uncover any additional relevant articles. Thus, the inclusion of *DfD* in the initial search query was evaluated to be unnecessary. To further evaluate the collected literature and determine the need for additional keywords, a word cloud was generated from the screened publications' keywords (see Figure 2). The word cloud in Figure 2, showing the 50 most utilized keywords, was generated using the wordcloud [26] matplotlib [27] Python packages. The keywords from all included articles were extracted and merged into a single list used to generate the word cloud. This visualization was refined by excluding common stop words to ensure only the most relevant terms were highlighted. This visual tool aided in identifying important terms that might have been overlooked.

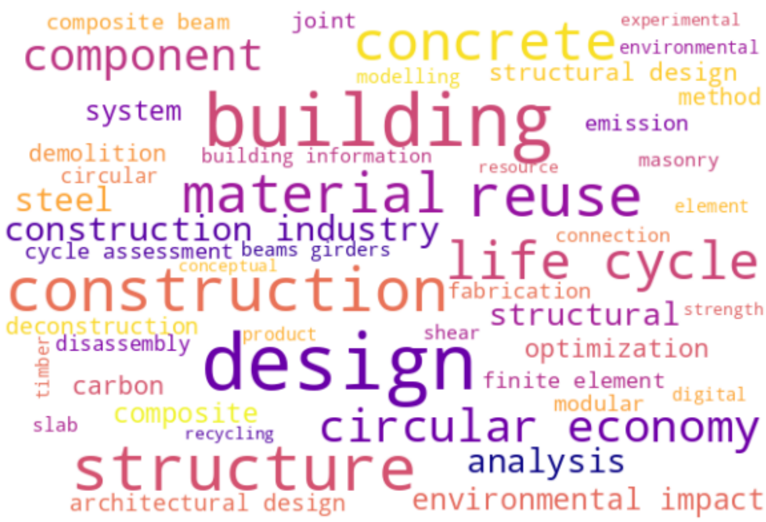


Figure 2. Word cloud illustrating the variation of keywords used in the screened publications.

In analyzing the word cloud, it became evident that the final collection covered a diverse range of topics, aligning with the scope of this systematic mapping. Given the study's aim and research questions, the breadth of topics covered was considered sufficient, indicating no further iterations of the search query were necessary.

3. Classification and Mapping Scheme

Subsequently, a thorough examination of the 91 publications was conducted to uncover themes and patterns to answer the research questions formulated in the Section 1.3. Five critical attributes were identified: Research Type, Circular Design, Contribution, Application, and Material. The attributes have been carefully selected to map out the research conducted in the field.

Mapping Scheme

More specifically, the upcoming section will detail the definitions of the attributes discussed. Each attribute is divided into four to seven subcategories, which classify each publication. These subcategories are listed in Tables 3–7, and the attributes are defined as follows:

*Research Type.*This attribute categorizes the articles according to the research types outlined in Table 3, which are defined by their methodological approach and the type of insights they offer. Moreover, in cases where two or more research types are present, the dominant research type is used for this attribute.

Circular Design. Furthermore, this attribute categorizes the articles based on which specific CE strategies within the topic of reuse in structural engineering are present. These specific strategies are listed in Table 4.

Contribution. This attribute refers to the type of contribution that the publication offers to the development of CE within structural engineering. The types of contributions range from digital innovations and structural solutions to insights into circular economies within building design, as specified in Table 5.

Application. For which parts of a structure is the CE strategy applied? This attribute examines how a CE is implemented in building design, including whether it pertains to the overall structural system, or to the level of structural components or structural connections, or generally concerns the building without specifying the structural application. See Table 6.

Material. The publications are also classified based on the specific material, listed in Table 7, in focus. For publications where there is no particular material discussed, 'Not applicable' is provided as an alternative.

Notably , all categories within *Circular Design* cover various strategies related to reuse. However, in subsequent sections, '*Reuse*'—as precisely denoted—will refer to the specific category defined in Table 4.

Furthermore, a content analysis based on the applied attributes was performed using NVivo to ensure a thorough and systematic evaluation. In Section 4, the results and a discussion of this analysis are presented.

Table 3. Research Type.

Review	Investigation of existing research within the scope.
Case Studies	Circular building design demonstrated in practical projects.
Technical Paper	Empirical research with in-depth structural analysis aimed at structural verification of technical solutions that facilitate CE.
Framework	Guidelines, strategies, and tools for establishing a workflow that facilitates circular building design. It is distinguished from 'Design Development' by its broader focus on conceptual and strategic planning, rather than direct advancements in structural engineering design practice.
Design Development	Development of innovative structural engineering methodologies for circular design, focusing only on the structural engineering practices themselves.

Table 4. Circular Design.

DfD	See definition of *DfD* in Section 1.2.
Reuse	Strategies for designing buildings from reclaimed material.
Upcycling	See definition of *Upcycling* in Section 1.2.
Deconstruction	See definition of *Deconstruction* in Section 1.2.
Reuse and DfD	Discusses both *reuse* and *DfD* in equal measure.
General CE	Where the concept of CE in building design is generally discussed, with no specific strategy in focus.

Table 5. Contribution.

Computational Design	Integrates computer-based structural engineering methods, employing algorithmic and optimization techniques for innovative structural methodologies enabling circular structural design.
Computational Tools	Digital aids assisting in modeling and management decisions outside the structural design practice itself, thereby facilitating the application of circular design.
Structural Concept	Development of specific structural designs that support CE.
CE investigation	Research not covered by the contributions mentioned above that offers insights through a discussion on CE in structural engineering.

Table 6. Application.

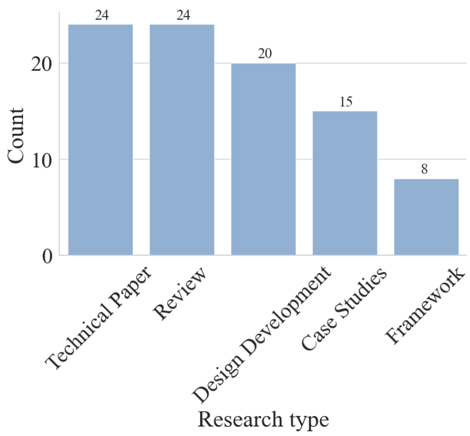
Connections	Focus on the design of structural connections.
Structural System	Focus on the entire structural system's design.
Structural Element	Focus on the individual load-carrying members within a structure.
General Building	Publications that fall outside the specific structural categories mentioned above, addressing the broader context of building design.

Table 7. Material.

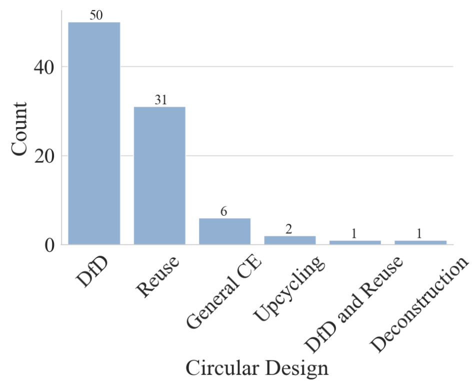
Steel	Structural steel.
Concrete	Structural concrete.
Timber	Structural timber and wood.
Composites	Integration of multiple materials within a structural solution, excluding processed composite materials like reinforced concrete, which fall under the concrete category.
Masonry	Structural masonry.
Other	Specific materials that are not included in the materials already listed in this table.

4. Results and Discussion

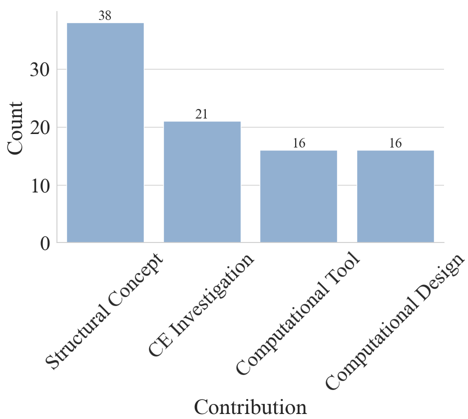
To address the research questions, the findings from the systematic mapping are further analyzed and discussed. Initially, Figure 3 illustrates the distribution of the attributes from the collected publications. This is followed by a closer examination of *Research Type* and *Circular Design*, both separately and in context with each other. To observe the developments and trends in this field, the findings for the attribute *Contribution* are further discussed, along with an overview of trends in *Materials* and *Applications*, concluding with the development over time.



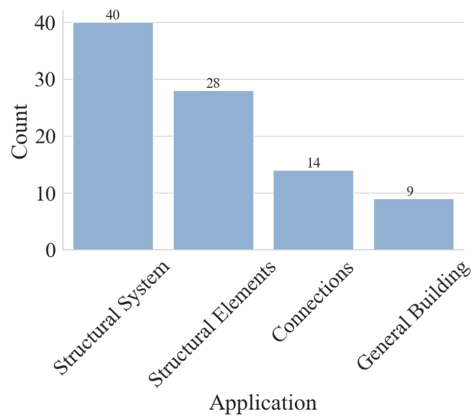
(**a**) Countplot of *Research Type* attribute



(**b**) Countplot of *Circular Design* attribute

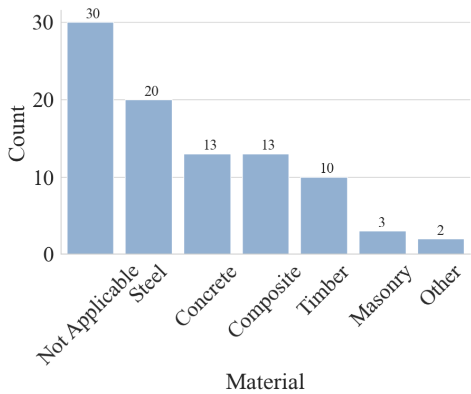


(**c**) Countplot of *Contribution* attribute



(**d**) Countplot of *Application* attribute

Figure 3. *Cont.*



(**e**) Countplot of *Material* attribute

Figure 3. Distribution of attributes in the included papers for all attributes.

4.1. Research Type

Examining Figure 3a, it can be observed that the subcategories of the *Research Type* attribute, namely *Reviews* and *Technical Papers*, are equally represented, accounting for 52% of the publications. *Design Development* closely follows, comprising 22%, underscoring innovative design methods in the structural engineering practice. *Case studies* account for 16% of the publications, which is substantial but a smaller proportion. Projects such as the circular building Petite Maison by Odenbreit et al. [28] showcase the significant resources required in such *case studies*, particularly when compared with *Reviews*, which rely on existing research and are typically less resource-intensive. Further, as *Framework* is defined in this study, the *Research Type* covers circular design strategies outside the development of structural engineering practices themselves. This may be the explanation for only 9% of the publications. However, the included *Framework* publications are highly relevant, featuring tools for facilitating structural circular design through strategic decision-making tools [20,29,30], the incorporation of Life Cycle Assessment (LCA) in building projects [16], LCA within a Building Information Modeling (BIM) environment to create materials banks for reusing structural elements [31,32], BIM features for circular design [33], and predictions of reusability with machine learning techniques [34]. Illustratively, Bertin et al. showcase a BIM-based material bank integrated approach for the anticipated reuse of structural elements, emphasizing LCA from design to construction.

4.2. Circular Design

In Figure 3b, it becomes evident that the *Circular Design* strategies *DfD* and *Reuse* dominate the field. *DfD* alone represents 55% of the literature, emphasizing its central role. *Reuse* strategies are also thoroughly explored, accounting for 34% of the publications. *DfD* and *Reuse* also reflect this focus, with both strategies being equally discussed within the same publications, where Gruter et al. investigate both strategies to facilitate the circular use of timber elements [35]. Papers on *General CE* are less common, but still account for 7%. *Upcycling* and *Deconstruction* are included in 2% and 1% of the literature, respectively. Yang et al. discuss the application of building *Deconstruction* for prestressed structures, aiming to facilitate the reuse of structural elements from such structures. As this is the only article on *Deconstruction* [17], the topic within the CE of the building industry could emerge as being more relevant for stakeholders involved in the practical deconstruction process rather than in structural engineering. Thus, throughout this section, the category *Deconstruction* is not further discussed.

4.3. Research Type and Circular Design

The combination of *Research Type* and *Circular Design* is visually represented in a bubble diagram, shown in Figure 4. As previously stated, it is evident that *DfD* and *Reuse* are the most common Circular Design strategies in the study scope. Furthermore, the diagram shows that the majority of the publications are *Technical Papers* on *DfD*. The publications in this area typically focus on conducting technical assessments, verification, and performing calculations for structural elements and connections designed for easy disassembly for future reuse [25,36–54]. A plausible reason for this trend could be that it addresses a clear problem with easily accessible technical solutions, which enables significant advancements in the field without requiring extensive adjustments to current design practices. The same applies to *Case Studies*, where the majority of publications also relate to *DfD*. Given that the *Technical Papers* provide *DfD* solutions, it is not surprising that the same approaches are tested in *Case Studies*.

Distinct from traditional technical solutions in structural engineering, the *Upcycling* category solely comprises *Case Studies* that explore innovative and less traditional ways of dealing with limited material resources in the building industry. The publications either demonstrate structural systems made from bicycle frames [55] or structures created out of magazines [56]. This may explain the relatively small proportion of articles within the *Upcycling* category, as it represents more idealistic and unconventional approaches compared with the traditional technical solutions in structural engineering.

Considering Figure 3, it is expected that *Reviews* on both *Reuse* and *DfD* will be predominant, as *Reviews*, along with *Technical Papers*, are the most common *Research Types*. Reviews typically identify and discuss trends within the study's scope, thus covering the most prevalent trends, *DfD* and *Reuse*. Additionally, within the *Circular Design* attribute *General CE*, the majority of publications are *Reviews*, providing a broader discussion on the topic of the CE in structural engineering [57–60].

Another interesting observation that Figure 4 shows is that *Reuse* within *Design Development* is the second-largest group. Contrary to the theory that explains the large number of *Technical Papers* on *DfD*, one could interpret this amount of research as a need for development beyond current design methods to achieve the reclaiming of existing materials. In traditional structural design practice, a concept is designed and the materials are selected thereafter. However, in the case of reusing structural elements, the materials are to some degree fixed and the concept must be designed accordingly. This perspective is elaborated on by Brütting et al. in their series of publications [61–65]. In this case, *Reuse* requires a change in structural design practice: a need for *Design Development*.

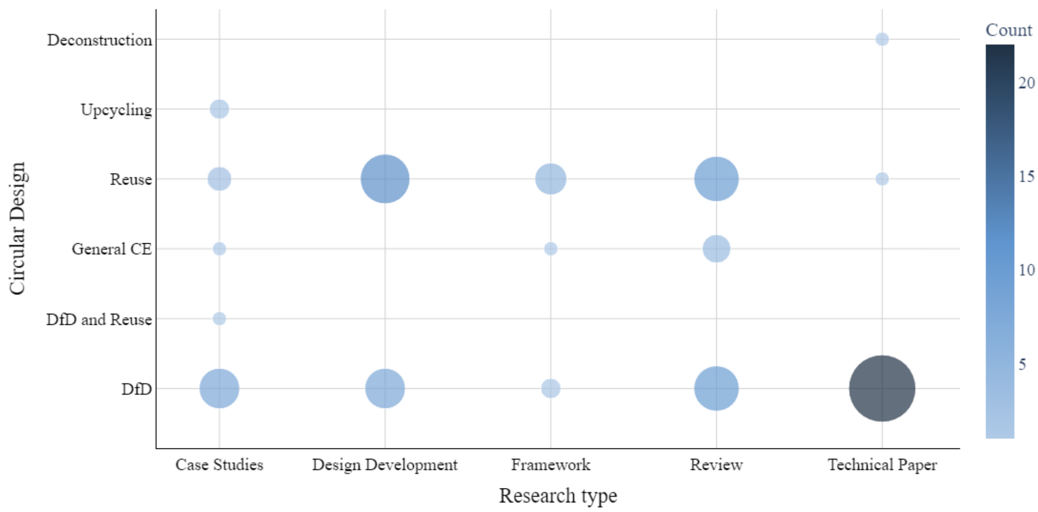


Figure 4. Distribution of publications by Research Type and Circular Design.

4.4. Research Contribution

Furthermore, the *Contribution* attribute classifies the publication based on what type of development the research contributes. This includes whether it provides pure insights through *CE Investigation*, the development of *Structural Concepts*, innovative design methods in *Computational Design*, or facilitating circular design through *Computational Tools*.

Figure 5 highlights a notable concentration of *Structural Concepts*, with 37 articles predominantly within *Technical Papers* and *DfD* strategies. This pattern is consistent with the previously discussed trend of technical solutions for structural systems designed for future reuse (*DfD*), with Yang J et al. contributing significantly to this area [28,37,45,66,67]. Notably, *Structural Concepts* are also prevalent in *Case studies* and *Design Development* in combination with *DfD*.It is as well as the only *Contribution* for the less represented *Circular Design* strategies: *Upcycling*, *DfD* and *Reuse*, and *Deconstruction*. This is not surprising, as the development of *Structural Concepts* aligns with the core focus of structural engineering. However, for the Circular Design attribute *General CE*, the majority of articles fall within the *Computational Tool* [16,58,59,68]. These articles discuss the application of technology in terms of digital tools to achieve CE principles in structural engineering, without intended specific CE strategies.

Following closely with 21 publications, *CE Investigation* discusses the integration of CE principles, trends, and gaps in the research area. This naturally results in a majority of *Review* publications, aligning with previous patterns, giving an even distribution between *DfD* and *Reuse*. The topics emphasized are LCA [21,57,69–71], adaptability [21–24,57,69,70,72,73], and the potential of *CE integration* within specific materials like *concrete* [18,22,24,74], *timber* [23,75], and *steel* [73,76–80], which is further explored in Section 4.5. Additionally, through the further examination of publications within the *CE investigation*, the recurrent critical research gaps have been identified as the need for precise standardization [21–23,57,74,77,78,81], digital tool integration [81], and overcoming challenges in policy [69,76,78], market acceptance [73,78], and industry-wide adoption to advance CE [18,22,72,74,75,82].

Figure 5. Swarm plot presenting the categorization of publications with respect to Research Type, Circular Design, and Contribution.

Through the observation of the *Contribution* attribute in combinations of *Research Type* and *Circular Design*, the majority of *Computational Design* mainly lies within *Design Development*, specifically focusing on *Reuse*. An interesting discovery is that *Brutting* together with *Fivet* author 50% of the *Design Development* publications [10,61–65,83,84]. Their work explores innovative computational approaches to structural circular design practices, employing methods such as mixed-integer linear programming for structural optimization [61,62], structural stock optimization [61–63], form finding, and parametric optimization [83], while emphasizing LCA [62,63] with a particular focus on truss structures [61,62,64,65,83]. Moving beyond *Computational Design*, *Brutting* and *Fivet* have also contributed to five additional publications on similar themes [20,49,74,85,86], establishing them as leading contributors in the publication collection.

The remaining eight publications within *Computational Design* also address optimization [60,87], mixed-integer linear programming [88], and parametric design [89], in addition to techniques for non-standard elements [90–92], interlocking design [93], and design for rapid fabrication [94,95].

As elaborated in Section 4.1 and illustrated in Figure 5, the publications within the category *Framework* are the main contributors to *Computational Tools* involving BIM, LCA, and decision-making tools. Hence, Figure 5 shows that the most significant digital developments are occurring within *Design Development* and *Framework*, collectively offering the potential for a digital design workflow for circular building design.

The results presented in Figure 5 are further illustrated in Table 8, where references to all articles are included.

Table 8. Mapping of the articles based on *Circular Design* (vertical left column), *Research Type* (horizontal bottom row), and their *Contribution* (see footnote).

Deconstruction					SC: [67]
Upcycling	SC: [55,56]				
Reuse	SC: [85,96], CE: [79]	CD: [61–65,87–92,97]	CT: [20,30–32,34]	CD: [62,84], CE: [18,70,73–76,78,80]	CE: [98]
General CE	CT: [68]		CT: [16]	CE: [57], CT: [58,59], CD: [60]	
DfD and Reuse	SC: [35]				
DfD	CT: [94,95,99], CE: [71], SC: [66,100–102]	CD: [83,93], CT: [103], SC: [15,86,104–106]	CT: [29,33]	CE: [21–24,69,72,77,81,82], SC: [19]	SC: [17,25,28,36–54]
	Case Studies	Design Development	Framework	Review	Technical Paper

CT = Computational Tool, CD = Computational Design, SC = Structural Concept, CE = Circular Economy Investigation.

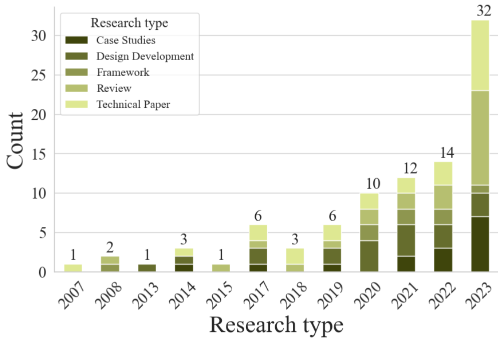
4.5. Development Area

The attributes *Material* and *Application* emphasize the focus on physical aspects within CE in structural engineering and are essential for addressing research questions as well as understanding development trends.

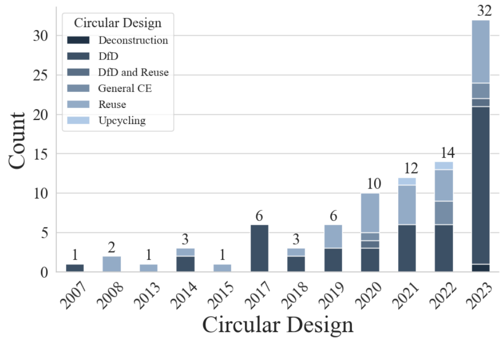
Initially, the findings from these attributes are illustrated in Figure 6, which also presents the time series of all attributes. The diagram includes all publications and highlights an exponential growth in the number of publications in recent years, with a particularly notable increase after 2020. This trend emphasizes how initiatives like the European Green Deal have increased the industry's focus on CE principles [57].

Examining the publications per year by the *Materia*l attribute in Figure 6e, *Concrete* has shown steady development. There has been a significant increase in *Steel* since 2022, paralleled by research in *Composite* materials. Notably, *Timber* saw a drastic rise in 2023. Reflecting on Figure 3e, the majority of the publications address *Steel*, with 22% of the publication collection, with *Composite* and *Concrete* each accounting for 14% of the studies. *Timber* accounts for 11%, while *Masonry* and other materials represent 4% and 2%, respectively. It is noteworthy that 33% of the publications do not discuss a specific material and are categorized as *Not Applicable*.

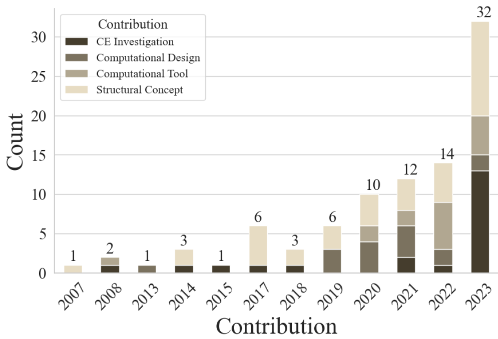
In terms of *Application*, there has been proportional development within the categories over the years (see Figure 6d). *Structural Systems* and *Connections* together have been predominant since 2017. Upon examining the *Circular Design* trends in Figure 6b, it suggests a potential correlation with the focus on *DfD*, where *Structural Systems* with *Connections* that allow for disassembly are emphasized. This could also explain the prominence of *Steel* and *Composite* materials, typical for prefabricated systems, which facilitate easy assembly and disassembly. Likewise, the *Application Structural Elements* development over the years aligns with the trend in *Reuse*.



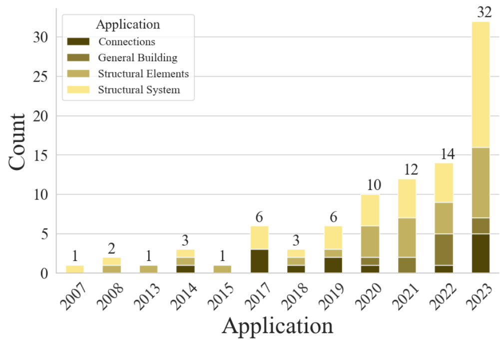
(**a**) Development of publications for the *Research Type* attribute



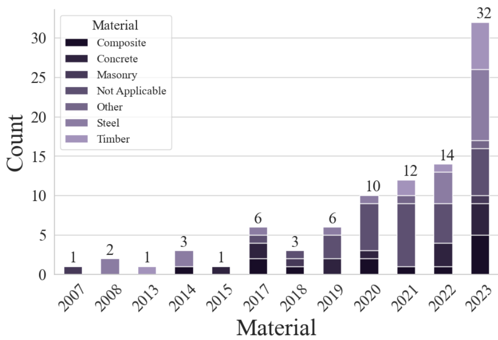
(**b**) Development of publications for the *Circular Design* attribute



(**c**) Development of publications for the *Contribution* attribute



(**d**) Development of publications for the *Application* attribute



(**e**) Development of publications for the *Material* attribute

Figure 6. Development in yearly publications for each of the five attributes.

5. Conclusions

This study has carried out a systematic mapping of the circular economy (CE) in the context of Structural Engineering. Given the notable increase in attention toward sustainability and CE in the construction industry over the last few decades, there is a need for systematic mapping to evaluate the current landscape. The attributes used were defined in order to address Section 1.3. The main findings are summarized as follows:

- The research landscape is diverse; however, reviews and technical papers make up more than half of the literature collected. There is a strong focus on technical solutions for demountable connections that facilitate the future reuse of structural materials, elaborated through structural calculation and empirical testing in technical papers. A high amount of review papers reveal an exponentially growing interest in CE within structural engineering, identifying key trends and critical gaps. The recurrent gaps identified in the literature are the need for more comprehensive standardization, the enhanced integration of digital tools, and overcoming challenges related to policy, market acceptance, and industry-wide adoption. Articles about design development, constituting 22%, also highlight the need for advancements in structural engineering practices to achieve CE in the industry.

- The predominant trends within CE strategies in structural engineering emphasize Design for Disassembly and Deconstruction (DfD), which alone represents over 50% of the literature. This suggests that the development related to reuse primarily focuses on the potential for future reuse and represents a more accessible strategy for implementing CE in the construction industry. However, strategies for integrating reclaimed materials into building designs are thoroughly investigated through the development of innovative computational practices in structural engineering. The research on upcycling and deconstruction remains limited, indicating potential areas for further development. It could also reflect a limitation in the collected literature, potentially due to the choice of keywords in the search query. However, the topic of upcycling and deconstruction is not necessarily relevant on its own, but becomes pertinent due to its context in reuse and structural engineering. This supports the accuracy of the observations regarding the low representation of relevant articles on upcycling and deconstruction in the field.
- Innovations in structural engineering have become increasingly evident through digital developments. Algorithmic design methods, such as mixed-integer linear programming and parametric optimization, enhance reuse through innovative design approaches. Computational tools, particularly those integrating Building Information Modeling (BIM) and Life Cycle Assessment (LCA), play a crucial role within the research field. They enable the creation of digital material banks for available reclaimed elements and facilitate strategic decision-making processes.
- Steel stands out as the most investigated material in this context, demonstrating a central role in DfD strategies. The emphasis on timber has notably increased, especially in 2023, highlighting its growing relevance in sustainable structural systems. Research on concrete and composite materials within the CE in structural engineering has consistently shown a steady trend, with a focus on adaptable structural systems.

Based on the insights from this systematic mapping, the study identifies the following research gaps and thereby the necessities for future research. A further literature review that delves deeper into the potential of computational design methods, as revealed in this systematic mapping, could be a valuable direction for future work. Furthermore, the next step toward achieving sustainable building designs based on CE principles involves the integration of structural engineering methods as digital tools within a common digital environment. A digital framework that enables structural engineers to seamlessly integrate designs from reclaimed elements and DfD into an effective digital workflow for conventional building design is essential. As part of this framework, the research points to the need to develop a standardized digital material bank for assessing and classifying the quality of reclaimed materials as critical. The material bank should aim to contain complete information, suitable for determining the structural performance for safety purposes as well as for providing an accurate digital representation for design. Therefore, we conclude that a digital framework, including a comprehensive, standardized material bank along with advanced computational methods for design from reclaimed elements and DfD within a common digital environment, is crucial for advancing circular structural design in the future.

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writing—review and editing, S.M.H., M.L. and H.R.S.; visualization, S.M.H. and H.R.S.; supervision, M.L.; project administration, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

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