IOP Conf. Series: Earth and Environmental Science **1363** (2024) 012040 doi:10.1088/1755-1315/1363/1/012040

Design for Disassembly and Reuse: A Synthesis for Timber Construction

T O Chiletto[1], E Knapen[1] and R N Passarelli[1]

[1]Faculty of Architecture and Arts, Hasselt University, Hasselt, Belgium

tatianadeoliveirachiletto@uhasselt.be

Abstract. A global demand has emerged for a paradigm shift in the construction industry. In favour of sustainable practices, there is an increasing focus on timber applications. In this context, both academics and practitioners have begun to explore ways to implement new strategies leading to circular use, such as Design for Disassembly and Reuse (DfD&R). This paper aims to investigate scientific publications reporting on recent and emerging debates and practices in the field of DfD&R with a focus on timber construction. For this purpose, a meta-synthesis of a systematic literature review was used. This procedure allowed the collection, classification, and critical appraisal of 71 scientific articles published over the last two decades. By categorising the articles into main content categories and subcategories, their main approaches and methods could be systematically classified and critically analysed. The results showed what types of research are being produced, what aspects they are considering, and, within the life cycle of a building, what stages they are covering. As a result, this synthesis has highlighted the main focus in the field, leading to an understanding of the trend in recent studies. This article synthesises research in the field, contributing to the transition to circular timber building.

1. Introduction

The construction sector is responsible for a substantial part of resource consumption, waste generation and greenhouse gas emissions [1]. Therefore, global awareness is emerging, urging a paradigm shift in the construction industry to favor sustainable practices, with a growing focus on timber applications [2]. Wood is touted as a promising raw material for achieving circularity in the building sector, providing an opportunity to switch to construction methods that are naturally renewable but still provide the expected building performance [2]. However, shifting to renewable building materials alone does not tackle the issue of resource consumption and waste production entirely. A more responsible strategy for using timber is also imperative.

Currently, most buildings are demolished at the end of their lifespan. And the common use of non-reusable and irreversible connections between materials leads to pollution and permanent material loss [3]. Reusing construction materials can be a suitable alternative, but it may require extensive processing or grading of the materials and components. The deconstruction processes may not be possible if the parts are glued together or connected with 'wet' joints. This can make them both economically unattractive and technically unfeasible [4]. According to the data presented by Akinade et al. [5], less than 1% of existing buildings are fully demountable. The authors suggest that despite the principles of deconstruction design known for the past 20 years, current deconstruction methods demonstrate that the approach is yet to achieve its full potential.

The strategies of designing for deconstruction are not new and are associated with the principles of the Circular Economy (CE). There has been an increase in the amount of information available on CE principles [6, 7, 8, 9, 10], and different CE frameworks in the construction industry have emerged [11, 12, 13, 14, 15]. In this context, both academics and practitioners started looking into ways to implement those strategies leading to a circular use of materials, such as Design for Disassembly and Reuse (DfD&R). With an increasing number of DfD&R initiatives, it is imperative to comprehend present advancements in the construction industry to analyse and grasp the situation of DfD&R practices. More specifically, in the complex environment of the timber construction sector, there is a need for a broader understanding of opportunities and good practices, that could support a more coherent application of its methods.

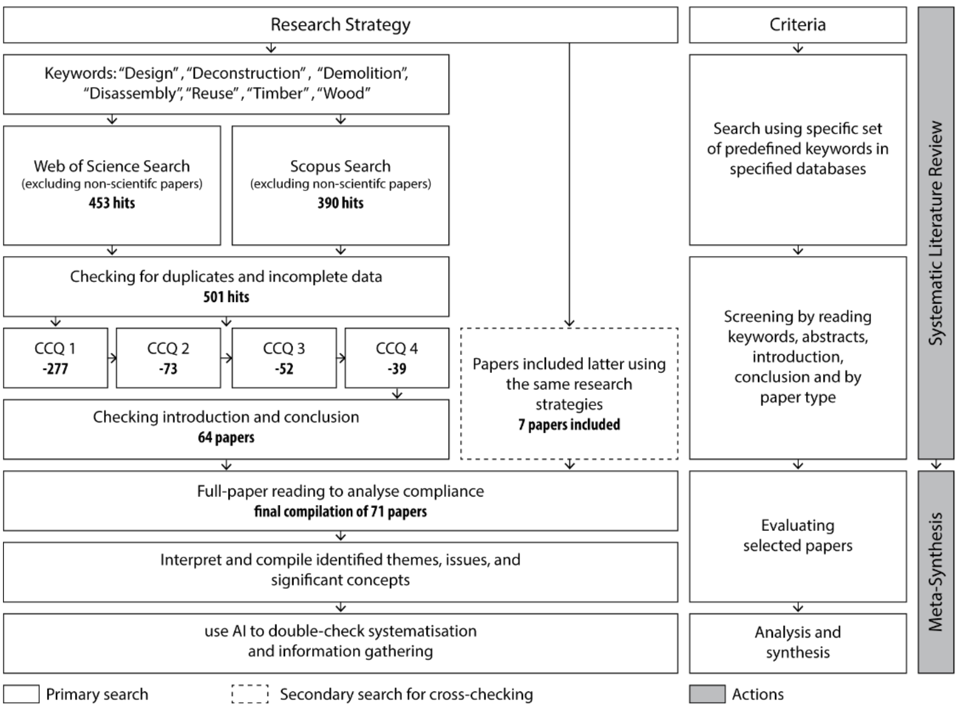
Therefore, this paper aims to investigate scientific publications that report recent and novel debates and practices in the Design for Disassembly and Reuse field for timber construction. For this purpose, a meta-synthesis from a systematic literature review was used. The meta-synthesis was not intended to be an exhaustive study to define Design for Disassembly and Reuse. It intends to represent state of the art for DfD&R analysis within timber research. The procedure allowed the definition, classification, and critical assessment of 71 scientific articles published over the last two decades.

The meta-synthesis helped to understand how to integrate and analyse findings from multiple studies to derive overarching themes and insights on the topic. This approach identified recent studies on the topic and provided a comprehensive understanding of the current state of knowledge in the field. Valuable insights can be offered in areas where further research is needed. This can guide future studies and contribute to the continuous improvement of design practices in timber constructions for academics and practitioners.

2. Methods

The approach to explore the DfD&R studies on timber construction was split into two stages. First, a Systematic Literature Review (SLR) was applied to gather the articles pertinent to the topic, as shown in Figure 1. A meta-synthesis was then developed to review the compiled data.

Figure 1. Systematic Literature Review Approach



Systematic Literature Review

Briner and Denyer [16] presented a protocol to conduct a systematic review with stages in eight steps: (1) background review that justifies what will be studied; (2) definition of the objective; (3) criteria definition from considering studies, that delineate the types of researches that will be included in the review; (4) strategy definition to obtain the studies, according to which databases will be selected; (5) eligibility review, that excludes studies which do not meet predetermined standards; (6) data collection, describing how the data will be obtained; (7) quality assessment method review, that evaluates the quality of the collected data; (8) results synthesis. Based on that, the process can be summarised as follows:

1. **Problem statement:** "What are the main possibilities, challenges, emerging trends, and scientific focus for design for disassembly and reuse in the context of timber structures?".
2. **Objectives:** to identify the recent papers in the current literature on Design for Disassembly and Reuse strategies in the building sector, focusing on what is being published for timber structures.
3. **Criteria:** a search within the "article title, abstract, and keywords" in Scopus and Web of Science.
4. **Search strategy keywords:** "Design", "Deconstruction", "Demolition, "Disassembly", "Reuse", "Timber", and "Wood".
5. **Eligibility:** selecting both qualitative and quantitative research, case studies, experimental studies, and conceptual papers on DfD&R with timber; selecting publications from 2002- 2022; selecting peer-reviewed articles and conference papers that contribute valuable insights to the field; excluding non-timber focus; excluding articles for which the full content is unavailable.
6. **Data collection:** executing the search strategy across the selected databases, keeping records of the number of results from each source.
7. **Methodological Quality:** checking for duplicated articles and reading the introduction and the conclusion for compliance analysis. Then, closed-ended (yes/no) Compliance Check Questions (1-4) were used. If the answer to any question is "No", the publication was excluded from the final selection.
    1. Is the publication about DfD&R of timber in construction?
    2. Is the role of wood/timber construction significant in the publication?
    3. Is the publication about wood/timber as a structural building material?
    4. Is the publication about the design, construction, or end-of-life phases?".
8. **Synthesis:** conducted by a meta-synthesis analysis.

The rationale for adopting the SLR is that it uses explicit and transparent techniques to carry out a comprehensive literature search and critical appraisal of individual studies, and it systematically evaluates and interprets prior literature based on research objectives and questions [15, 16].

Meta-synthesis

The meta-synthesis allowed the definition, classification, and critical assessment of 71 scientific articles published in the last two decades. The approach was chosen to zoom out from individual studies and provide a more comprehensive overview. The articles were categorised into main content categories and subcategories. The following steps were conducted:

1. Full-paper read to ensure compliance and evaluation of the scope of the papers.
2. Analysing and sorting publications into categories to establish noteworthy and recurring patterns in the findings. The sorting was based on [17]:
    - **Level of application**, i.e., if the strategy addresses the overall building, component, or product level.
    - **Level of readiness**[1], i.e., if the paper has a theoretical, experimental, simulation or consolidated basis.

[1] This paper uses the following definitions: "Theoretical" - related to theoretical research, e.g., research papers discussing general concepts and ideas; "Experimental" - research with a practical application, e.g., prototypes

- **Methods**, as explicitly determined by the authors in the papers.
- **Category**[2], i.e., if the paper is a fundamental or applied research.

3. Interpret and compile within the context of the compiled lists.
4. Double-checked sorting analysis via SciSpace by Typeset (AI-powered).

3. Results and Discussion

A summary with the final 71 research papers selected was developed to provide an overview, systematise, and facilitate comparison between the body of research on DfD&R strategies and concepts for timber construction. Appendix A shows the analysis map according to the selected literature. Within each of the analyses, the application and reading levels were organised as follows:

1. **Level of application:** to what extent do building, component and product applications mentioned in the text?
    - 0 = does not appear.
    - 1 = is mentioned in the text.
    - 2 = appears but is not the main subject.
    - 3 = is the main object of study.
2. **Level of readiness:** to what extent are the following aspects studied in depth:
    - Theory: 1 = quotes essential concepts and definitions; 2 = explores important concepts and definitions; 3 = produces qualitative analysis.
    - Simulation: 1 = cites an assessment tool; 2 = uses an assessment tool, but it is not the main goal; 3 = use the assessment tool as the primary method.
    - Experiment: 1 = cites a hands-on experiment; 2 = use a hands-on experiment, but it is not the main goal; 3 = use the hands-on experiment as the primary method.
    - Consolidated: 1 = mentions real-life case scenarios; 2 = analyses real-life buildings or uses reused/recycled components/materials; 3 = applies the DfD&R solutions in real-life constructions.

The articles were categorised into fundamental (8 hits - 11,27%), primarily fundamental (3 hits - 4,23%), applied (31 hits - 43,66%) or primarily applied (20 hits - 28,17%) research. Some papers included both fundamental and applied research (9 hits - 12,68%). The aim of this classification is to provide a clear and comprehensive scheme for various studies and their applications. It was used as a starting point to organise the studies and was further used to catalogue the publications, which can be seen in Figure 4.

In terms of readiness level, see Figure 2, most articles (81,69%) use theory to some extent, but it is not their main focus. Only 21 articles have theory as their primary topic. These articles explain, discuss, and develop relevant concepts on the subject. Simulation studies were the main focus in 47,89% of all papers, appearing in 34 out of 71 analyses. Only 20 papers (28,17%) focused primarily on experiments. For consolidated cases (76,06%), most articles studied real-life buildings or used reused or recycled components or materials (35 hits - 49.30%). Out of the 71 articles analysed, only 26 utilised experiments, making it the least used approach.

Lastly, at the level of application, see Figure 3, 42 of the articles analysed the building level as the primary subject of study. This was followed by the component level, which was the focus of 22 studies. Finally, the product level was discussed in 36 studies.

Overall, several research methods have been used in the studies, including case studies that use life cycle assessment or other circularity assessment (23,33%), case studies (22,22%), literature review

and test-/pilot projects; “Simulation” - research papers dealing with structural behaviour simulation, environmental impact, or circularity assessments, e.g., life cycle assessment; “Consolidated” - studies with real-life cases.

[2] This study uses the term "Fundamental" to describe research that aims to increase knowledge and comprehension by exploring theoretical concepts and underlying principles. The term “Applied” is used for those that focus on practical problem-solving and finding real-world solutions.

(12,22%), surveys or interviews (12,22%), lab experiments (6,67%), field survey (4,44%) or other methods (5,56%). Some sources do not explicitly mention the specific methods used (13,33%); in those cases, the categorisation was created through the details provided in the papers. Notably, some academic papers incorporate literature reviews, particularly for introductory purposes. As the literature review is not the primary output of those studies, this is not mentioned as research method in Table 1.

Figure 2. Level of readiness data

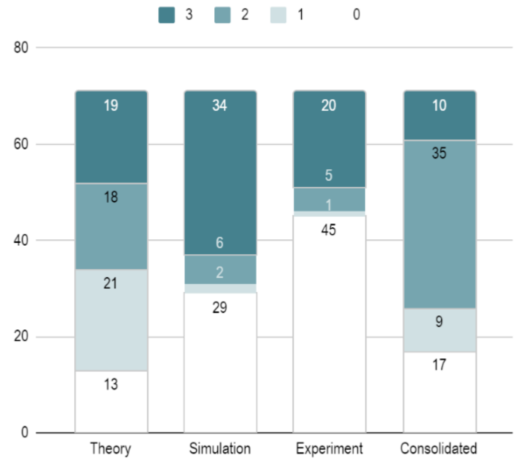
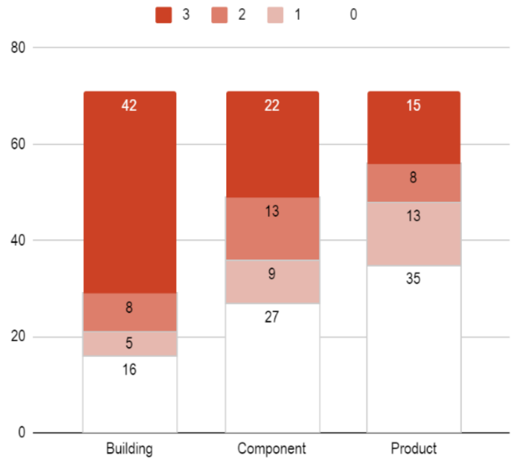


Figure 3. Level of application data



With this approach, it was possible to create a diagram to visualise the collected data, Figure 4. The diagram was created by grouping the different research categories aiming to find patterns. Considering the **applied** category, the main focus is the "Building" application, which is the most common of the three classifications. "Component" occurs more frequently than "Products", with the latter appearing very little in the analysis. "Simulation" readiness is a key topic in numerous instances, signifying a noteworthy focus on simulation in these publications. Some publications also demonstrate a strong presence of "Consolidated" readiness, but this varies. On the other hand, "Theory" and "Experiment" are less common.

The **primary applied** category strongly focuses on the "Component" application and the "Experiment" readiness. Additionally, both "Simulation" and "Theory" readiness are crucial factors in these publications. "Theory" appears frequently but only explores essential concepts and definitions. Following, the **primary fundamental** indicates a significant emphasis on the "Product" level", and less emphasis on the "Building" level. Both "Consolidated" and "Theory" play a prominent role in these publications. "Experiment" readiness does not appear.

In the **fundamental** category, there is a focus on the "Product" level and a strong emphasis on the "Theory" level of readiness, followed by "Consolidated". "Building" and "Component" applications are indicated in a few cases. "Simulation" and "Experiment" readiness does not appear. Finally, regarding both category, there is a strong focus on the "Building" application, with "component" and "products" varying. For the level of readiness, the focus on "Theory" is predominant and "Consolidated" appears, even if it is not explored as much. When "Simulation" appears, it is the primary research focus, with little emphasis on "Experiment".

4. Implications and Conclusions

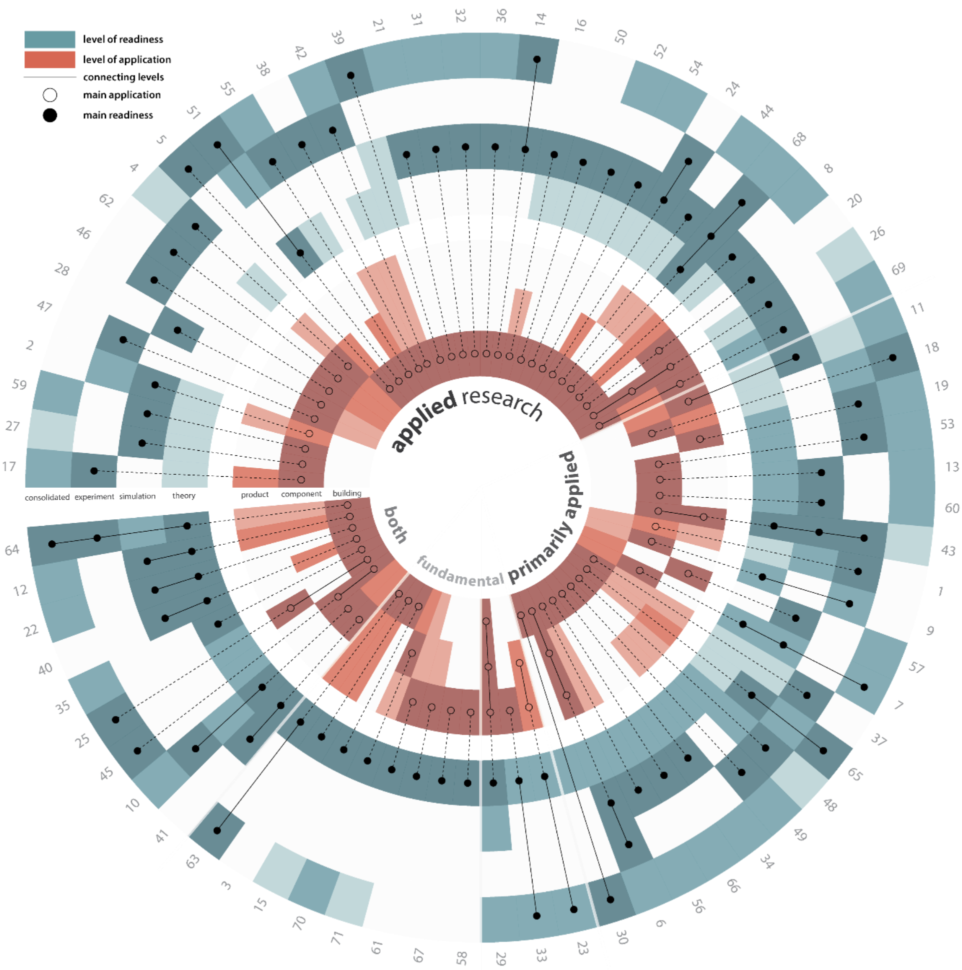
In the current context, academics and practitioners have started looking into ways to implement design for circularity strategies, aiming for a more circular use of wood in construction. In the past 20 years, Design for Disassembly and Reuse (DfD&R) has been a field of a growing body of knowledge.

By categorising the articles into main content categories and subcategories, their main goals and methods could be systematically classified and critically analysed. This is important to show what types of research are being produced, what aspects they are considering, and, within the life cycle of a building, what stages they are covering.

Overall, the selected papers address the concepts of DfD&R with a predominant focus on technical aspects using applied research methods. The categorisation indicated a predominance of LCA analysis and case studies in applied research, indicating a tendency towards technical and environmental analysis and a focus on the component level. Fundamental research and literature reviews remain limited. Ossio et al. [15] argue that a comprehensive understanding of the advantages of CE principles is crucial in overcoming obstacles to their adoption in construction. Therefore, there is further opportunity to explore the main possibilities of DfD&R for mass timber structures, considering its full potential and implication.

Choosing a systematic literature review, with a meta-synthesis as a start point, can help to build a bridge of knowledge, and provide a comprehensive overview of DfD&R in further research. The meta-synthesis helped to identify common patterns, themes, and trends across the 71 different studies. Since there is a need for a more holistic comprehension of trends, challenges, opportunities and pressing knowledge gaps that support further research, diffusion of knowledge and decision-making, this paper contributes to the transition towards circular timber constructions. The insights in this paper open new prospects to develop more comprehensive and integrated strategies, leading to better decision-making and ultimately improving the reuse potential of timber components.

Figure 4. Meta-synthesis data visualization



Acknowledgments
This study was supported by the Special Research Fund (BOF) of Hasselt University. BOF number: BOF23OWB02.

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Appendix A

Table 1. Meta-synthesis overview according to the selected literature

Nº	Category	Level of application			Level of readiness				Method 1	Method 2
		Building	Component	Product	Theory	Simulation	Experiment	Consolidated		
1	primarily applied	1	2	1	1	2	3	0	life cycle assessment	other
2	applied	0	2	1	1	3	2	0	lab experiments	-
3	fundamental	3	2	2	3	0	0	0	literature review	-
4	applied	2	3	1	1	0	3	1	not explicitly specified	-
5	applied	3	1	0	0	0	0	3	case study	-
6	primarily applied	3	3	3	2	3	3	2	literature review	life cycle assessment
7	primarily applied	2	3	0	2	2	0	2	life cycle assessment	-
8	applied	3	2	2	1	3	0	2	life cycle assessment	-
9	primarily applied	1	3	0	2	0	2	1	not explicitly specified	-
10	both	2	3	0	3	2	3	2	literature review	lab experiments
11	primarily applied	0	2	3	1	3	1	2	not explicitly specified	-
12	both	3	2	2	3	3	0	2	life cycle assessment	literature review
13	primarily applied	0	3	0	2	3	0	2	life cycle assessment	-
14	applied	3	0	0	0	3	0	3	lab experiments	-
15	fundamental	3	0	0	3	0	0	1	case study	-
16	applied	3	1	0	1	3	0	0	life cycle assessment	-
17	applied	0	3	2	1	0	3	2	case study	field survey
18	primarily applied	0	3	2	1	0	2	3	case study	literature review
19	primarily applied	0	0	3	2	0	3	2	case study	-
20	applied	3	0	3	0	3	0	0	life cycle assessment	-
21	applied	3	0	0	0	3	0	2	life cycle assessment	-
22	both	3	0	0	3	3	0	2	life cycle assessment	-
23	primarily fundamental	0	2	2	2	0	0	2	interview	-
24	applied	3	2	0	1	3	3	0	not explicitly specified	-
25	both	3	0	3	2	0	0	1	case study	-
26	applied	3	3	3	1	3	0	1	case study	-
27	applied	0	3	0	1	3	0	1	lab experiments	-
28	applied	1	3	0	0	3	0	0	case study	other
29	primarily fundamental	3	3	3	3	2	0	2	case study	life cycle assessment
30	primarily applied	3	0	0	2	0	0	3	field survey	-
31	applied	3	0	0	0	3	0	2	life cycle assessment	-
32	applied	3	0	0	0	3	0	2	life cycle assessment	-
33	primarily fundamental	0	0	3	2	0	0	2	literature review	-
34	primarily applied	3	0	0	2	3	0	2	literature review	case study
35	both	3	0	0	3	0	0	2	interview	survey
36	applied	3	0	0	0	3	0	2	field survey	life cycle assessment
37	primarily applied	3	1	1	1	1	3	0	lab experiments	-

Nº	Category	Level of application			Level of readiness				Method 1	Method 2
		Building	Component	Product	Theory	Simulation	Experiment	Consolidated		
38	applied	3	1	1	0	0	3	0	case study	-
39	applied	3	0	0	1	1	0	3	case study	-
40	both	3	2	0	3	3	0	0	not explicitly specified	-
41	both	2	3	0	3	3	0	0	case study	-
42	applied	3	1	1	1	0	3	2	not explicitly specified	-
43	primarily applied	0	3	3	3	3	3	1	literature review	life cycle assessment
44	applied	3	0	1	1	3	0	2	life cycle assessment	-
45	both	3	3	0	2	0	0	3	case study	semi-structured interview
46	applied	2	3	0	0	0	3	0	not explicitly specified	-
47	applied	1	3	0	0	0	3	0	lab experiments	-
48	primarily applied	3	0	1	2	2	3	1	case study	-
49	primarily applied	3	0	1	2	0	3	2	not explicitly specified	-
50	applied	3	0	0	1	3	0	2	life cycle assessment	-
51	applied	3	0	0	3	0	2	3	survey	-
52	applied	3	0	0	1	3	0	2	life cycle assessment	-
53	primarily applied	0	3	0	2	0	3	2	not explicitly specified	-
54	applied	3	0	0	1	3	0	2	life cycle assessment	-
55	applied	3	2	0	1	0	3	2	not explicitly specified	-
56	primarily applied	3	1	1	2	3	0	2	life cycle assessment	-
57	primarily applied	2	0	3	0	3	0	2	life cycle assessment	interview
58	fundamental	0	0	3	3	0	0	0	semi-structured interview	literature review
59	applied	0	3	0	1	3	0	2	case study	-
60	primarily applied	0	3	0	2	3	0	2	case study	-
61	fundamental	0	1	3	3	0	0	0	survey	-
62	applied	2	3	0	0	0	3	0	case study	-
63	fundamental	3	2	2	3	0	0	3	interview	-
64	both	3	1	1	3	2	3	3	other	-
65	primarily applied	3	1	2	1	3	2	3	life cycle assessment	-
66	primarily applied	3	0	0	2	3	0	2	case study	-
67	fundamental	0	0	3	3	0	0	0	not explicitly specified	-
68	applied	3	0	1	3	3	3	2	not explicitly specified	-
69	applied	3	2	3	2	3	0	2	literature review	interview
70	fundamental	2	3	1	3	0	0	2	literature review	case study
71	fundamental	1	1	3	3	0	0	1	interview	other

The list of bibliographical references analyzed is numbered in the following according to the order given in Table 1.

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