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Creating a Roadmap Towards Circularity in the Built Environment

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Chapter 6
Design for Disassembly and Reuse of Timber in Construction: Identification of Trends and Knowledge Gaps

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Abstract The transition to a circular economy (CE) offers an alternative path to the current linear, high-polluting, and wasteful practices in construction. In this context, there is a growing interest in studying the potential environmental benefits of extending the lifespan of renewably-sourced wood-based building products through reuse. However, most publications still fail to present a conceptually integrated and comprehensive view of the topic that allows for a broader understanding of its possibilities and challenges. This paper assesses two decades of literature on DfD&R of timber in construction. It develops a comprehensive state-of-the-art framework about the topic, unveiling its most critical challenges, trends, and pressing knowledge gaps. The outcomes of this work contribute to determining more integrated strategies and decision-making tools that could point to further development in the field of timber construction from a DfD&R standpoint, thus facilitating the transition to a CE.

Keywords Circular economy · Wood construction · Timber · Design for circularity · Deconstruction · Disassembly reuse · End-of-life · Literature review

6.1 Introduction

The transition to a circular economy (CE) offers an alternative path to the current linear, high-polluting, and wasteful practices in construction [1]. According to the definition from the Ellen McArthur Foundation, a CE is "restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times (…)" [2]. Through the implementation of a CE, the Circle Economy (2022) estimated that up to a 31% reduction in the emissions associated with the housing industry is possible if two conditions are met: (1) increased use of circular building materials and (2) more resource-efficient construction practices. In

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a nutshell, the CE message is that the inner circles of a product lifecycle demand fewer resources and energy than conventional recycling of materials for low-grade raw materials or their energy recovery [3].

Hence, the hierarchy for a CE indicates that recovering materials for reuse is a priority. Likewise, the European Directive on waste [4] urges the recovery of material waste streams through reuse and recycling as essential to limiting the extraction of virgin resources and, thus, reducing the environmental impact of construction. In this context, several publications studied the potential environmental benefits of extending the lifespan of renewably-sourced wood-based building products through reuse or recycling [5–7]. A number of studies also warn of the unforeseen challenges in pursuing an increased material cascading [8–12]. However, most publications still fail to present a conceptually integrated comprehensive view on the topic that allows for a broader understanding of its state of art, trends, challenges and opportunities, and pressing knowledge gaps that could support better decision-making and facilitate the transition towards a CE.

This paper aims to answer the following research question: what are the main trends, knowledge gaps, most critical challenges, and possibilities for DfD&R with wood in the current literature? To reach its goal, this paper assesses two decades of literature on the DfD&R of timber in construction, thus developing a comprehensive framework about the state-of-the-art on the topic. The results of this paper are relevant to both scholars and practitioners working in the field as they contribute to identifying significant gaps in scientific research and practical implementation of DfD&R with timber, which could contribute to developing more integrated strategies and decision-making tools, thus facilitating the transition to a CE.

6.2 Materials and Methods

This paper develops a comprehensive and systematic literature review method, followed by quantitative data analysis and qualitative interpretation. Firstly, the author retrieved all relevant scientific publications in English on the topic from 2002 to 2022. The publications were retrieved from the Scopus and Web of Science (WoS) databases, as the first contains the most relevant and high-impact publications in the field; the second comprises a larger database of indexed publications, including high-impact conference proceedings. Hence, the combination of the databases provides a comprehensive overview of the scientific developments in the field. Search string (1) was used for the papers sampling, excluding review papers and book chapters to focus on original scientific publications. Nonetheless, the search string was intentionally broad to yield the highest number of samples possible.

(1) *Design* AND *Deconstruction* OR *Disassembly* OR *Reuse* AND *Timber* OR *Wood*

In total, 843 publications were collected and checked for duplicates, resulting in an initial selection (IS) of 513 items. Then, the author refined the IS further through

a manual screening of titles and abstracts to check for compliance with the main topic of DfD&R of timber in construction. The compliance check consisted of four sequential closed-ended questions (Yes/No). If the answer to any question was No, the publication was excluded from the final selection (FS). Conversely, all the publications included in the FS answered Yes to all four questions. After the content compliance check, the FS consisted of 83 publications. The four questions with their respective intents and number of publications filtered are displayed in Table 6.1.

Next, the author assessed the metadata of the publications in the FS quantitatively. The values analyzed were the number of publications, type (journal or conference paper), year published, the total number of citations, first-author country of affiliation, and keywords. The analyses aimed to identify general trends related to the publications on the topic of DfD&R of timber in construction in the last two decades. Then, the author developed a qualitative content analysis of the FS based on the abstracts and full-text reading when needed to categorize the publications into distinct primary and secondary content groups and approach types. The qualitative content assessment aimed to expose the main subjects already covered by the literature, the density of

Table 6.1 Compliance check questions, intents and number of filtered publications

Questions		Intent	513 (IS)
1	Is the publication about the DfD&R of timber in construction?	To filter publications that, despite containing all search terms, had no connection to the topic and were, for example, coincidental hits when one of the authors had the word wood as part of his/her surname	−274
2	Is the role of wood/timber construction significant in the publication?	To filter publications that, despite mentioning the words wood or timber, were focused on other materials. The role of wood/timber was considered significant when at least one fiber-based case study at the component or building level was present in the publication	−68
3	Is the publication about wood/timber as a building material?	To filter publications that investigated wood/timber at the fiber or molecule level or for uses such as formworks, scaffolding, interiors, and furniture	−51
4	Is the publication about the design, construction, or end-of-life phases?	To filter publications that did not deal with the DfD&R of timber in the phases mentioned above and focused on the laboratory testing or verification of assemblies and solutions pre-defined elsewhere	−37
			83 (FS)

knowledge in each category or subcategory, and its most relevant existing knowledge gaps.

The DfD&R approaches identified were downstream and upstream. According to Piccardo and Hughes [12], downstream approaches relate to activities occurring after the end of life concerning the salvage process of wood products from buildings being disassembled or demolished and their posterior reuse in new buildings, whereas upstream refers to strategies developed in the early stages of design to facilitate the future reuse of wood products at their end-of-life. The three primary content categories definitions were based on the working groups' division of the ongoing COST Action 21103 (Implementation of Circular Economy in the Built Environment). The 11 secondary content categories were defined iteratively during the in-depth reading of the abstracts of the publications in the FS. The content categories and their respective subcategories are displayed in Table 6.2.

In a subsequent study, all publications will be fully read. This last in-depth full-paper analysis aims to identify and theorize the main challenges, opportunities, insights, and pressing tasks yet to tackle related to the DfD&R of timber in construction. That will lead to a comprehensive framework for understanding the current state of the art in the topic, thus contributing to more integrated strategies and decision-making tools that could point to its further development.

6.3 Results and Discussion

6.3.1 Metadata Analysis

Figure 6.1 reveals that the first publication retrieved dates from 2006, despite searching for studies since 2002. Moreover, the number of publications remained low for ten years, averaging 1.8 per year. Next, the figure shows a short transition period from 2016 to 2018, with an increase in interest in the topic and an average of five publications per year. Then, we notice a sharp growth in the number of publications in the last four years, with an annual average of 12.5. That attests to the remarkably recent and yet booming interest in the subject. Also, the share of journal publications (J) outgrew the number of conference papers (C) in recent years. Assuming that journal publications frequently require more accurate data and in-depth studies, they indicate the ripening of the topic as a sound scientific field. The increasing number of citations in the same period also supports this argument.

Figure 6.2 shows that publications in the FS originated from 27 different countries, 19 in the European continent, 4 in Asia, 2 in North America, and 2 in Oceania. However, the share of publications per country is unequal, with more than half (44) of all publications coming from only one-fifth (6) of the countries. This unbalanced distribution indicates that the knowledge development on the topic is still highly concentrated. Specifically, Germany and the USA led the research on DfD&R of timber, accounting together for 18 publications (22%). It is perhaps no coincidence

Table 6.2 Definitions of content categories and subcategories

Categories		
1. Strategies and best practices: Includes publications that deal with innovative methods to apply DfD&R strategies in design and construction activities and identify best practices	**2. Stakeholder engagement**: Includes publications that analyze the value chain of DfD&R solutions from the standpoint of key stakeholders	**3. Performance indicators**: Includes publications that employ relevant, reliable, and replicable quantitative performance indicators to measure the benefits of timber DfD&R solutions in construction
Subcategories		
1a. Urban scale: Comprises publications dealing with strategies and best practices on the urban scale	**2a. Politic**: Comprises publications engaging political stakeholders, such as representatives from the public sector or legislators	**3a. Environmental assessment**: Comprises publications that developed a quantitative environmental impact assessment, such as LCA (lifecycle assessment)
1b. Building scale: Comprises publications dealing with strategies and best practices in the building scale	**2b. Economic**: Comprises publications engaging economic stakeholders, such as investors and customers	**3b. Cost assessment**: Comprises publications that developed a quantitative cost assessment, such as LCC (lifecycle costing)
1c. Component scale: Comprises publications dealing with strategies and best practices in the building component scale	**2c. Technical**: Comprises publications engaging technical stakeholders, such as designers or contractors	**3c. Circularity assessment**: Comprises publications that developed a quantitative circularity assessment, such as material input–output rate
1d. Other strategies: Comprises publications dealing with advanced strategies and best practices, such as BIM, computational design, automation processes, or robotics		**3d. Other assessments**: Comprises publications that developed other quantitative assessments, such as mechanical testing, thermal, or energy simulations

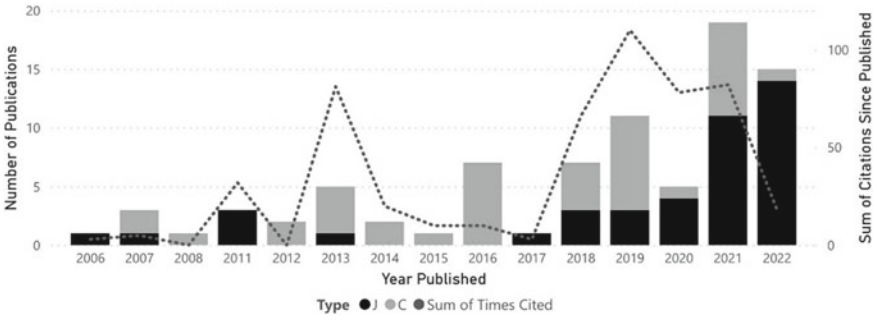

Fig. 6.1 Number of publications per year, per type and sum of times cited since published

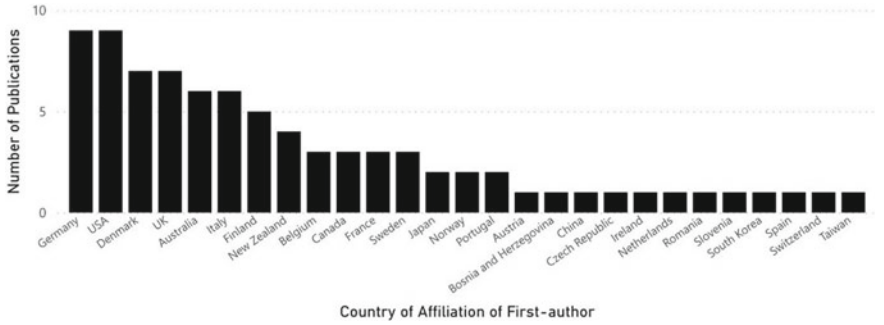

Fig. 6.2 Number of publications by country of affiliation of the first-author

that both countries hold the biggest GDP in their regions, with likely more access to funding, but also where the effects of a linear economy might be more visible. Next, we witness Denmark and UK tied in second place, with seven publications each. Australia and Italy follow closely with six publications each. It is also noteworthy that the list of origin countries in Fig. 6.2 only portrays so-called developed nations, except for one publication from China. Hence, developing countries in the global south are greatly underrepresented, despite sometimes hosting emergent timber construction industries such as Chile and Brazil. Although the scope of this study is insufficient to infer the reasons for this situation accurately, we can speculate they might include less availability of research funding, limited awareness or know-how on the topic, or even a language barrier for publishing in English.

Figure 6.3 shows the keywords assigned by the authors of the publications in the FS with an incidence higher than two. All keywords with identical meanings but different spellings were manually checked and adjusted to the same convention to ensure a fair assessment. For example, Building Information Modeling was rewritten as BIM. Not surprisingly, Circular Economy was the most popular keyword. The keyword Design for Disassembly (10) followed with a higher incidence than the keywords Reuse (6) and Material Reuse (3) altogether. This outcome suggests that researchers may be more prone to study the topic from an Upstream approach, as discussed in greater detail in item 3.2. The third most popular keyword was Life Cycle Assessment (9), which anticipates that this assessment method might be the prominent indicator to demonstrate the benefits of DfD&R quantitatively, as seen in item 3.2. It is also noteworthy that Cross Laminated Timber was the only product name to emerge on this list, hinting at the high relevance of mass timber construction in the topic.

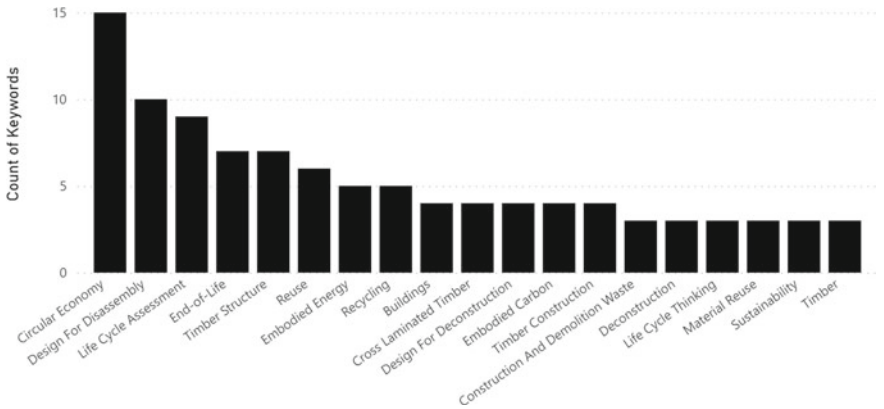

Fig. 6.3 Count of keywords assigned by the authors of the publications with incidence $n > 2$

6.3.2 Content Analysis

Overall, the content analysis revealed a balanced outcome in terms of approaches: 44 publications investigated DfD&R of timber from an upstream standpoint, 37 downstream, and three from both. It is important to note that publications in the last type analyzed both approaches as independent options. None of the publications in the FS investigated the link between upstream and downstream, thus confirming the knowledge gap previously uncovered by Piccardo and Hughes [12], mentioned in item 1.0. Nevertheless, we notice a new tendency when laying the approach distribution chronologically. Figure 6.4 shows a significant increase in the incidence of upstream-oriented publications in the latter half of the timeline. From 2006 to 2014, the share of upstream was 35%, whereas from 2015 to 2022, it almost doubled to 65%. That attests to a recent trend of considering DfD&R of wood/timber as a more integral part of the initial design task. On the other hand, that also indicates a diminishing interest in how to reuse the stock of materials already allotted to a building, thus neglecting to some extent the possibility of extending their service life span and trimming the need for extracting new resources, even if fiber-based renewed ones.

Figure 6.5 (left) shows that the primary content of publications in the FS deals predominantly with category 1 of Strategies and Best Practices (47), followed by studies on category 3 of Performance Indicators (29), whilst category 2 of Stakeholder Engagement was the last popular content (7). In category 1, publications tended to focus on subcategory C of the component scale (19), followed by the building scale subcategory B (15). Finally, the analysis found few publications that studied strategies and best practices related to the advanced topics in subcategory D, such as BIM and computational design, which might be a consequence of the relative novelty of such fields. Moreover, this study also revealed that a limited number of publications engaged with stakeholders as their main content. In category 2, subcategory C was predominant over the other subcategories, denoting a preference or convenience

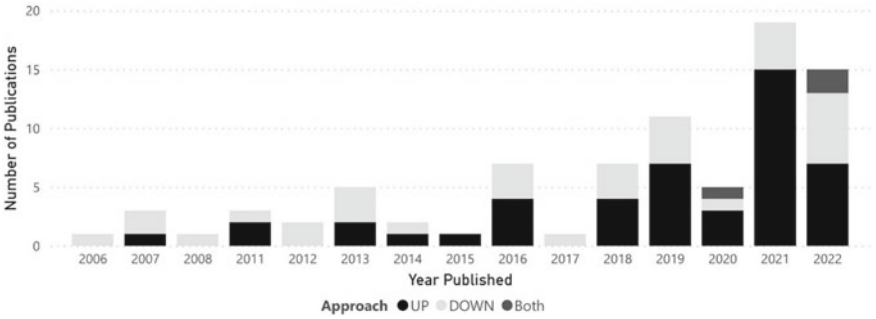

Fig. 6.4 Number of publications by year, by type of approach

for engagement with technical stakeholders. It is noteworthy that no publication engaged with economic stakeholders (subcategory B) and only one with a political stakeholder (subcategory C), which exposes a significant knowledge gap for the future implementation of these practices, for even when there are possible technical solutions, there still needs to be political will and economic feasibility. In category 3 of Performance Indicators, subcategory A of environmental assessment methods was dominant with 19 publications, often using the LCA method, characterizing it as the key indicator currently to measure the benefits of timber DfD&R. The predominant choice for LCA as an assessment method might be the consequence of a lack of alternative standard-defined methodologies to measure the circularity of buildings and components. Nonetheless, subcategory C of circularity assessment with six publications suggests that, although still limited, there is interest in experimenting with original quantitative methods to measure the circular benefits of timber DfD&R in construction.

Figure 6.5 (right) shows that the secondary content of publications in the FS is quantity-wise comparable between categories 1 (22) and 3 (18). Category 2 was once again the last popular content (3). Differently from the primary content outcome,

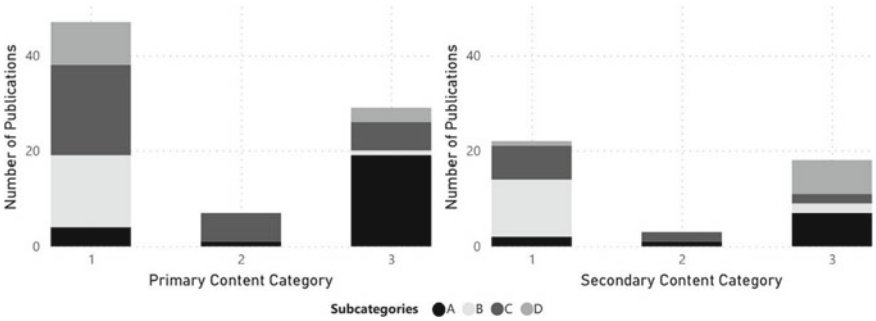

Fig. 6.5 Number of publications by content categories and subcategories. Primary publication content (left); Secondary publication content (right)

publications with secondary content in category 1 focused on subcategory B (12), followed by subcategory C (7). Furthermore, an even more limited number of publications engaged with stakeholders (category 2) as their secondary content, 2 in subcategory C and 1 in A. Once again, no publications engaged with economic stakeholders (subcategory B). Finally, the publications that introduced category 3 as secondary content were evenly distributed between subcategories A and C (7 each). Overall, the secondary content category of the publications in the FS maintained the same priorities as the primary content ones (Strategies and Best Practices and Performance Indicators) but presented a slightly more balanced concentration of the most prevalent subcategories (Building or Component Scale and Environmental or Circularity Assessment).

6.4 Conclusions

The metadata analysis showed growing interest and maturation of the topic, particularly in the last four years. Nevertheless, there is an accentuated tendency to focus on the upstream aspects of DfD&R of timber in construction. Although that is undoubtedly a critical task to produce more circular buildings in the future, there is a risk of neglecting enough attention to developing solutions to use the current stock of wood-based materials already trapped in our building stock. That would offer a counterpoint to the still linear mindset that we need to produce and build more, even if more sustainably, when, in fact, we need to do it less. Furthermore, this study confirmed a critical gap in publications linking upstream and downstream DfD&R approaches, for example, scrutinizing the true disassembly potential of allegedly demountable strategies. Finally, the metadata analysis also showed publications originated almost exclusively from so-called developed countries. Taking into account that developing countries are usually expected to experience faster growth, it is essential to ensure that it occurs with minimal impact. Furthermore, although the reasons for the lack of representation of developing countries are not evident in this study, the discussion on the decolonization of the narrative in the scientific field is imperative and long overdue. Even the simple inclusion of free-of-charge translation/revision services in big English language publishers could already contribute to giving voice to the countries absent in this narrative. Also, a more vigorous implementation of north–south co-developing research projects with specific grants for that purpose would be yet another way to empower underrepresented voices in the scientific field.

The content analysis uncovered that publications frequently seek to study innovative strategies and identify best practices for the DfD&R of timber in construction, particularly on the component scale. The choice for a smaller study scope may answer the academic need to minimize parameters to a managing point considering all the complexity in a building. Despite the fact this will surely yield in-depth results of critical individual aspects, that also indicates a significant knowledge gap related to the understanding of more holistic strategies on the building scale and an even more

substantial gap on the urban scale. The second most covered content was on performance indicators to measure the benefits of DfD&R strategies. There was, however, a clear predominance of LCA as the preferred method to measure the outcomes of timber DfD&R strategies. It is highly plausible that this is the consequence of LCA being a well-known standardized method to assess the environmental impacts of products or buildings. At the time of writing, there was no established method to measure the circularity of constructions defined by a international association such as the ISO, creating an additional barrier to researchers trying to venture into systematically assessing the circularity index of given solutions. Yet, this study identified a growing number of publications implementing novel methods to quantify the benefits of DfD&R strategies as its primary or secondary content. Although still in their infancy and lacking in number, these isolated publications attest to the relevance of developing a scientific method that is fit to assess the circular benefits of timber DfD&R in construction. Hence, this gap will most likely be gradually filled, especially after the new ISO standards on circularity, currently under development, are published. Finally, this study unveiled a substantial knowledge gap related to stakeholder engagement as a publication content, with only a few studies reaching out to representatives in the technical field. It is worth highlighting that no publications in the FS investigated DfD&R of timber from the standpoint of an economic stakeholder. Therefore, new publications on the topic should actively pursue higher exchange with key decision-makers in the field, particularly the ones such as investors and customers (economic stakeholders) or legislators and government representatives (political stakeholders).

The results of this study also have some limitations that can be addressed in new studies on the topic. Firstly, as the systematic review only covered scientific publications, there may be additional know-how to investigate in technical reports and published material from companies and practitioners that were not within the scope of this paper. Secondly, although the sampling criteria were defined as objectively and clearly as possible, the final selection and classification process is, to some extent, subject to personal bias. Finally, the sampling in this study only included search terms and publications in English. Hence, further studies can employ a similar methodology to explore the state-of-the-art of DfD&R with timber developed and published in other languages.

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