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Timber structures designed for disassembly: A cornerstone for sustainability in 21st century construction

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ABSTRACT

The need to reduce the construction industry's waste and greenhouse gas emissions has led the sector to advance towards the circular economy by adopting the Design for Disassembly (DfD) system, a philosophy that aims to produce easily recoverable products, parts and materials from dismantled, renovated or transformed structures. Applying the DfD philosophy to timber structures has garnered significant research attention thanks to its inherent modularity and renewability in a system perfectly aligned with DfD principles.

In this context, this paper reviews the existing literature on timber structures designed according to DfD standards, identifies its main research themes and highlights some of the current research gaps and challenges. The results of the study provide valuable guidance for researchers, practitioners and regulatory bodies involved in the design, construction and assessment of DfD timber structures and are expected to boost the system's implementation.

1. Introduction

The construction sector is responsible for approximately 35 % of the world's CO_2 emissions and contributes 45–65 % of landfill waste [1]. Furthermore, the industry's operations release a substantial volume of harmful emissions, accounting for roughly 30 % of the global greenhouse gases (GHG) [2]. The construction sector is also responsible for the consumption of 65 % of the world's total aggregates, 20 % of the metal [3] and 60 % of the raw material [4].

To reduce the environmental impact associated with the sector and improve its sustainability, it is essential to adopt the practices included in the Circular Economy (CE) [5]. These define a production and consumption model that entails the maximum of sharing, renting, reusing, repairing, renewing and recycling existing materials and products to generate added value and extend the lifecycle of its products. CE aims to reimagine and reintegrate the pre-industrial system of keeping materials and products at their maximum value across all the economic cycles. This approach offers an essential alternative to the prevailing linear production and consumption model [6] and has caused a shift in the construction sector from merely reducing the energy consumption of operational buildings to adopting a holistic approach that includes a building's entire life cycle [7,8].

Design for Disassembly (DfD) is thus the key to promoting CE in construction and involves a building design process that allows products, parts and materials to be easily recovered when a building is disassembled or renovated. DfD is intended to maximize economic value and minimize environmental impacts through reuse, repair, remanufacture and recycling and involves planning and designing in a way that facilitates smoother deconstruction. Deconstruction, which involves dismantling a building while preserving the

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usability of its materials, fundamentally alters the conventional waste management approach. Adopting DfD practices represents a significant strategy that safeguards raw materials and is considered a pivotal step toward sustainability [9]. The fundamental tenets of DfD include: 1) maintaining accurate documentation of the materials and deconstruction methods, 2) crafting accessible connections and joints to facilitate dismantling, 3) segregating any items that are neither recyclable, reusable nor disposable, 4) creating uncomplicated structures and forms that enable component standardization and dimensional consistency, and 5) designs that consider labor practices, productivity and safety [7,8].

The history of construction demonstrates that concrete and steel have played central roles in engineering and architectural projects [10–12]. However, cement production leads to GHG emissions, while recycling reinforced concrete is a challenge due to the recycled concrete-based materials losing most of the qualities and performance of their original counterparts [13]. Steel production also evokes significant environmental concerns as it generates substantial carbon emissions [14], even more so than in the case of concrete [15]. In contrast, timber is gaining popularity as a primary material for the new building paradigm since its carbon footprint is less extensive than that of reinforced concrete [16] and steel [17]. As timber products, including cross-laminated timber (CLT) and glue-laminated timber (GLT), sequester carbon, have less embodied carbon than concrete and steel, and can be repurposed and recycled multiple times before they have to be incinerated, their atmospheric carbon remains stored for extended periods [18]. The role of timber in the construction sector's sustainability can be further expanded by the wider application of CE and DfD principles, as several studies have shown (e.g. Refs. [19,20]). These papers confirmed the technical feasibility of using reclaimed wood. However, a great deal of the wood recovered from building construction and demolition is typically either incinerated to generate energy or is disposed of in landfills [21]. Only about a third of European construction and demolition wood waste is currently recycled into material for board products [22].

Thus, detachable timber structures, DfD and with reused timber seem to be one of the best options for improving the construction sector's sustainability. In this context, the present paper aims to promote cleaner construction practices by analyzing the current state of the art in key DfD aspects for timber structures and identifying areas in which further research is needed. The analysis is based on information gathered from 129 publications selected by the method described in Section 2. Section 3 examines the chronological and geographical distribution of these publications and identifies and describes the topics they cover. Finally, Section 4 identifies some of the research gaps found and Section 5 summarizes the main conclusions of this study.

2. Methodology

The literature review was conducted through a systematic multi-phase approach, aiming to include as many publications as possible and extract comprehensive information from them. The method followed is summarized in Fig. 1.

First, a keyword search was conducted in Scopus and Google Scholar using the keywords “timber” or “wood” and “design for disassembly”, “design for adaptability”, “design for deconstruction”, “deconstruction”, “disassembly”, “adaptability”, “reuse”, “demountable”, “deconstruction” or “detachable”.

Next, a “retrospective search”, which entailed choosing important references from the previous step was performed. A similar method was used in the subsequent “prospective” search phase, involving a search of the works that cited the references chosen from the retrospective search.

The final stage used Artificial Intelligence to extend the bibliographic search and validate the relevance of the available references on Inciteful software. This is a customizable tool that can use one or more seed articles (the tool suggests 5) to conduct a literature selection process [23]. The seed pool expanded as new papers were found that met the predetermined criteria, leading to the creation of a fresh network. This iterative process of paper selection and network expansion persisted until no additional papers were discovered that met the selection criteria. This citation analysis identified not only the most significant papers but also highlighted those that are most similar [23].

After analyzing the search results, a filtering process was performed resulting in the selection of 129 target studies, which were classified into different research fields according to the topics, issues or challenges they addressed. A final bibliographic review was then conducted to determine any gaps in the knowledge.

3. Review results

The literature review results are divided into topics of interest in timber structures DfD. The bibliometric analysis is first described, followed by a detailed examination of the research fields.

3.1. Bibliometric analysis

First, two key points were processed: year of publication and the country in which the research was carried out. Fig. 2 shows the distribution of published documents in the different decades, offering valuable insights into the evolution of research and the growth of interest in the topic. The first Investigations were in the 20th century, marked by the initial definitions of DfD concept. Research progress during the subsequent decade was relatively slow, with a total of 6 publications analyzed. However, after 2010, there was a more active and continued research effort, with a notable increase in publications that reached a total of 40 studies. In recent years, beginning in 2020, there has been a substantial surge in publications with 114 studies, which underscores the growing importance of the topic.

Fig. 3 gives the frequency of countries based on the number of published papers. Most of the research is concentrated in Sweden, showcasing the country's significant progress in the topic. This can be attributed to Sweden's robust wood engineering back-

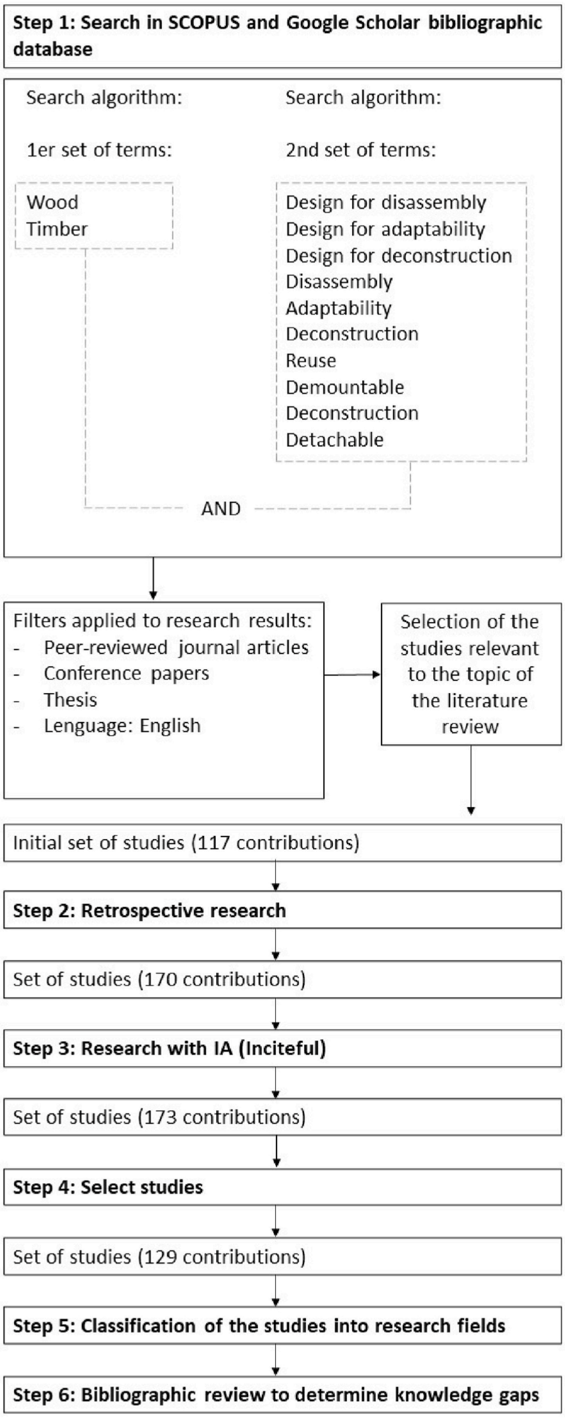

Fig. 1. Flowchart describing the method adopted for the literature review.

ground and the trust established throughout its forestry value chain [24]. Fig. 3 also reveals that Europe is the leader in the number of studies, accounting for 76 % of the publications.

Furthermore, a keyword map was created using Vosviewer software [25] with text data from the titles and abstracts that appeared in more than 10 of the 129 selected papers, an analysis technique used in recent literature reviews [26–28]. This system reveals the most extensively studied topics within a field, their interconnections and the identification of potential knowledge gaps. It should be noted that text data with equivalent meanings were grouped together to simplify visualizing the map. A total of 80 keywords met the threshold, as can be seen in Fig. 4. The larger the circles, the higher number of co-occurrences of the keywords, and the closer they

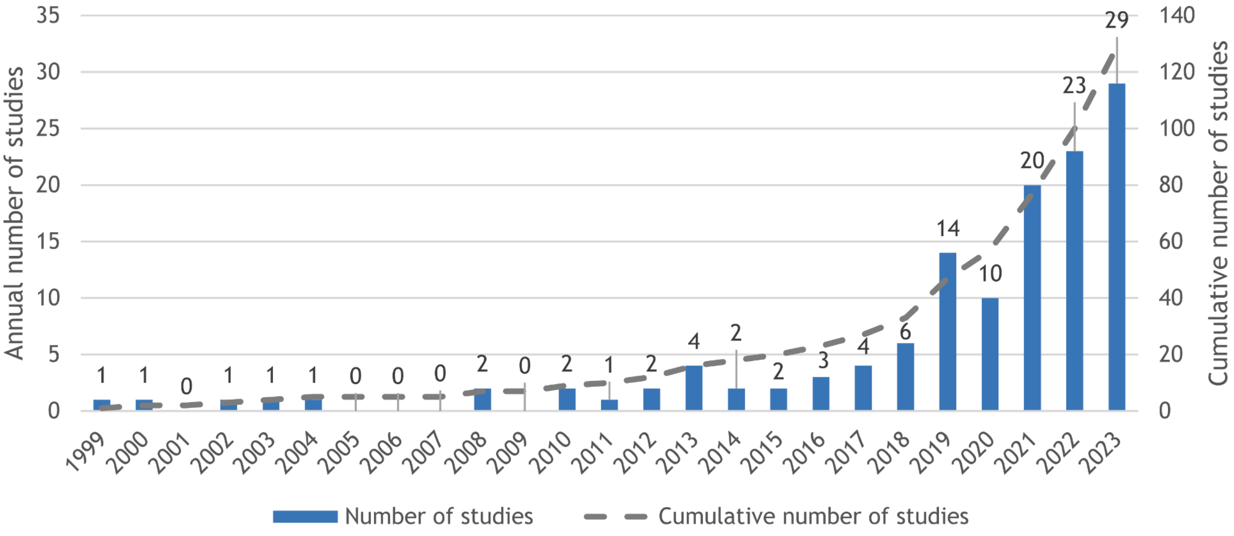

Fig. 2. Annual and cumulative study publications per year.

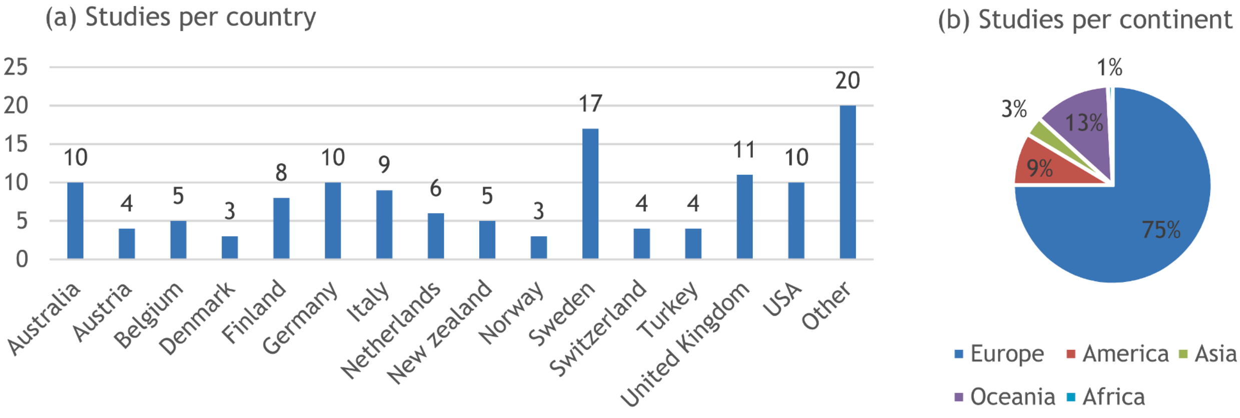

Fig. 3. (a) Studies per country. (b) Studies per continent.

are, the closer their relationships. Fig. 5 identifies the key research topics based on the results of Fig. 4 and a detailed review of the selected papers.

The following observations can be made:

- Keywords "timber", "reuse", "deconstruction", "circular economy" and "disassembly" are among the most frequent, since they coincide with some of the terms considered in the bibliographic research. Other common keywords are "timber construction", "connection", "life cycle assessment", "adaptability", "joint", "recycling", "framework" and "CLT".
- Early studies focus on terms such as "deconstruction", "demolition waste" and "recycling", while more recent articles emphasize "timber construction", "mass timber", "circular economy" and "connection". Important terms like "disassembly", "adaptability", "reuse" or "environmental impact" appear in between.
- DfD-related concepts such as "deconstruction", "disassembly", "recycling", and "reuse" are particularly significant, collectively addressed in 88 % of the publications (114 out of 129), as illustrated in Fig. 5.
- During the bibliographic search, the concept "Design for Adaptability" (DfA) emerged, sharing common aspects with DfD but will be discussed as a distinct concept later. DfA is less relevant than DfD, as it is discussed in 45 % of the reviewed publications (57 papers).
- "Sustainability", including ideas related to "environmental impact", "life cycle assessment", and the "circular economy", is another key theme. It is covered in 122 articles, accounting for 95 % of the total. "Construction methods", which include terms like "timber", "timber construction", "mass timber", "concrete", "cost", and "time", are discussed in 60 publications (47 %). Additionally, concepts related to structural analysis such as "CLT", "joint", "connection", and "screw", appear in 28 papers (22 %).
- The keywords "principle" and "framework", considered a key factor in defining a technology's degree of maturity, are discussed in only 24 papers (19 %).

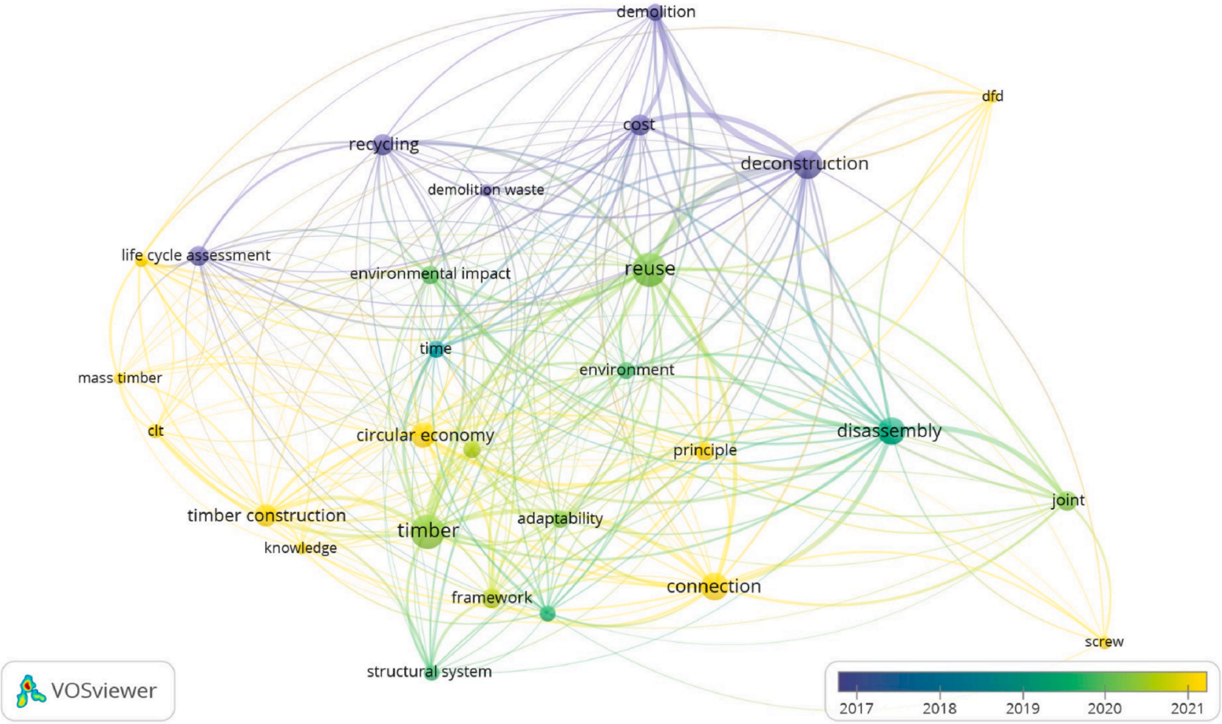

Fig. 4. Keyword map of the search results.

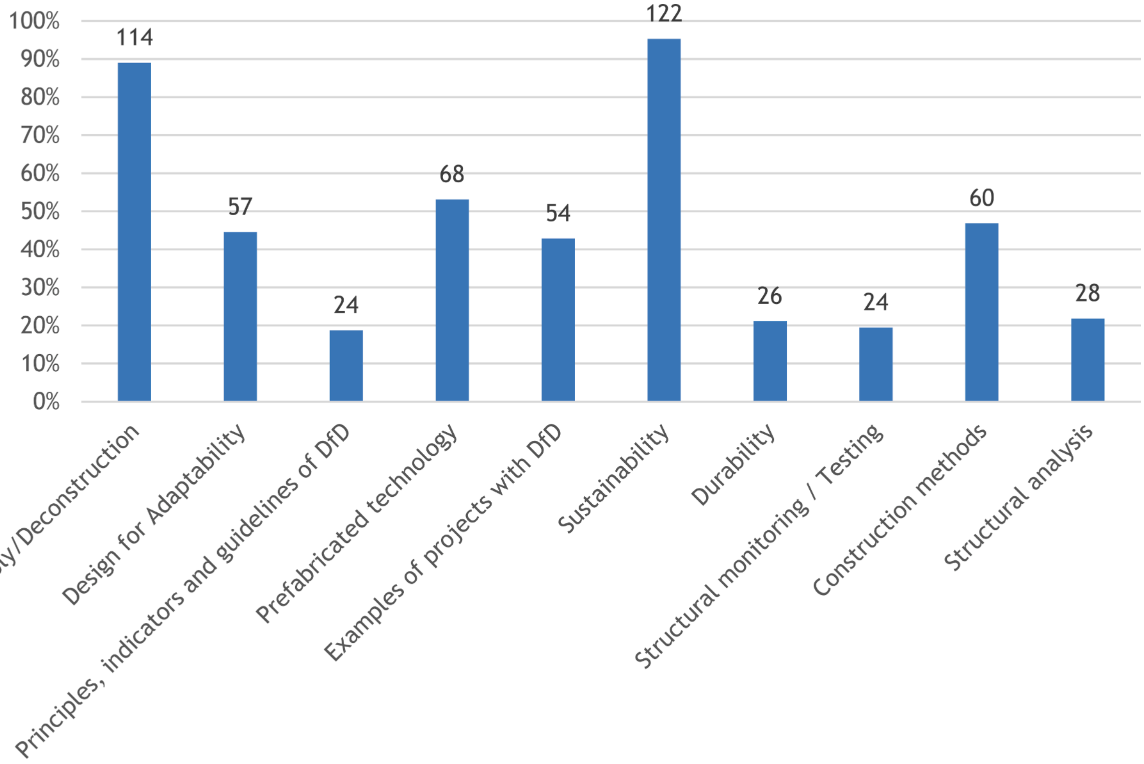

Fig. 5. Number of studies per research topics.

- The concept “Project examples” is not included in Fig. 4 because this term does not appear in the titles and abstracts, but rather becomes relevant from the fact of carrying out a bibliographic review. Case studies provide key insights into the development of the research topics. As can be seen in Figs. 5 and 54 (42 %) of the examined papers cover “Project examples”.
- Lastly, three prominent research topics emerged: “prefabricated technology”, “durability”, and “structural monitoring and testing”. While these topics are absent from Fig. 4, they are included in Fig. 5 due to their being generally accepted as potential research areas. Notably, “prefabricated technology” is acknowledged as a critical component of DfD in timber buildings [29–31], and is discussed in 68 publications. Furthermore, “durability” is discussed in 26 (20 %) publications, and “structural monitoring and testing” is covered in 24 (19 %) publications, both identified as essential DfD research areas and supported by several authors [32–34]. Consequently, dedicated sections have been allocated to these topics.

3.2. Research topics

3.2.1. Design for disassembly/deconstruction (DfD)

In one of the initial definitions of DfD Crowther [35] showed that materials, components, and whole buildings can go through several lives before they decline into waste and defined four strategies for their reincarnation in the building environment: relocation and reuse of the entire building, reuse of components in a new building or elsewhere in the same building, reprocessing the components and materials into new components and finally, recycling the materials into new components.

Many authors have supported the general DfD framework established in Ref. [35] and delved into the principles of circularity as applied to timber construction. Dams et al. [32] emphasized the central role of DfD and DfA in circular construction. This method ensures that building elements and connections can be disassembled, reused or rearranged beyond their initial design life. Vandamme and Rinke [36] also noted that circularity in timber engineering is primarily about DfD and focusing on components or materials regardless of their location within the building. In pursuit of sustainable construction, Van Houten [37] proposed combining mass timber (MT) with recyclable metals to create hybrid structures, advocating dismountable connections throughout the design to enable future disassembly. Kim and Kim [38] emphasized the significance of DfD in recovering reusable components from old structures, highlighting the importance of the early consideration of deconstruction. Sandin et al. [39] suggested designing buildings with reuse in mind to reduce material waste. Roithner et al. [40] advocated easy disassembly in building designs to enhance recyclability, while Psilovikos [41] demonstrated that reusing and recycling construction and deconstruction waste is feasible through the Design for Deconstruction and Reuse (DfDR) concept. Psilovikos [41] urged a review of European building codes to promote timber reuse. As proposed by Di Ruocco et al. [31], adopting dry technological construction systems (i.e, systems not using water during construction) in the design phase over wet ones (i.e. systems that require a significant amount of water), supports the potential for disassembly and reintroducing materials into the production cycle.

Several authors have highlighted the advantages of using wood as a construction material in conjunction with DfD. For instance, Schuster and Geier [42] emphasized the unique potential of timber construction for DfD and carried out surveys that acknowledged the disassembling potential of prefabricated building components, specifically noting the separability of individual component layers. These authors also pointed out that both disassembly and reuse following minor repairs or simply replacing the building elements, are viable and noted that DfD strategies face economic challenges due to their associated high labor requirements. Kissi et al. [43] revealed that common DfD principles include comprehensive documentation of materials and methods, the standardization of components, and a preference for mechanical over chemical joints. Diyamandoglu and Fortuna [44] argued that timber structures, especially residential buildings, represent a valuable source of second-hand construction materials in the United States. They advocated incentivizing and promoting deconstruction and reuse due to its clear benefits in reducing GHG emissions while generating economic advantages with ease of implementation. Piccardo and Hughes [45] pointed out that strategies related to DfD often adopt a systemic approach, with wood elements planned as interconnected parts of a building system that can adapt to future changes if this is planned during the design phase. These authors also proposed downstream and upstream approaches. Upstream strategies (activities occurring when a product that have not yet reached the end of live (EoL) yet) aim to facilitate the future reuse of wood elements in new buildings, while downstream strategies (activities occurring beyond the EoL of a product) focus on the reusing wood elements from demolished or disassembled buildings in new construction. These strategies involve numerous stakeholders in procuring, processing and final reusing salvaged wood through an iterative process led by designers. Implementing these strategies in timber buildings may be more complex compared than conventional wood use as they require specific expertise in disassembly and adaptability, as well as in the procurement of salvaged wood. The practice of reintroducing wood into new constructions is relatively recent and is often limited to “experimental” buildings, necessitating a strong commitment from the stakeholders. In this line, the performance of the material in new buildings is neither regulated nor certified.

Numerous authors have explored the environmental advantages of integrating wood into DfD structures. Di Ruocco et al. [31] emphasized the potential of DfD wooden buildings to became zero-emission constructions. Lehmann [46] highlighted how engineered wood products (EWP) used in structural frames and façade systems offer important environmental benefits including low formaldehyde emissions and have an inherent suitability. The use of these products also reduces resource consumption during the demolition stage. Al Shamaa and Saleh [47] demonstrated that adopting DfD principles benefits companies by achieving sustainable buildings, enhancing project value, and reducing material costs and waste. Various deconstruction and reuse scenarios were examined in Ref. [48], emphasizing the potential environmental efficiency of designing dismountable structures that allow component reuse or recycling.

Research in DfD timber field has also paid attention to the role played by joints and connections [33]. Sandin et al. [49,50] conducted a detailed deconstruction process of a timber structure, documenting valuable experiences that provide insights into what to avoid and what to encourage when designing timber buildings for future deconstruction and reuse, giving special importance to joints. Westerholm and Franssila [51] demonstrated a hybrid construction system based on mechanical metal connectors, allowing for easy assembly and disassembly. Promoting reversible design can also be initiated in the early project planning phase by mandating detailed demolition plans during the design stage and the use of mechanical joints. However, specific approaches are needed for timber due to its unique properties compared to abiotic construction products [29]. Smith et al. [52] documented the excellent seismic performance of a post-tensioned timber building designed with DfDR principles. Marmo [53] highlighted that properly designed structures for correct deconstruction should avoid the use of adhesives and chemical treatments. The choice of tenon and mortise joints with timber pegs becomes crucial in ensuring the dismantling of buildings and the reuse of construction materials. Regarding façade systems, timber nail connections were found to be highly efficient during disassembly, proving to be the quickest way to disassemble during EoL activities. However, the disassembled panels retained holes from the nails, which could pose challenges for potential reusability. In contrast, façade systems with a geometric assembly (i.e. those featuring milled mullions and no connectors at all), did not encounter this issue [54].

Innovations have been carried out in DfD timber structures in recent years. Derikvand and Fink [55] have taken a proactive stance in advocating for the adoption of DfD principles in timber–concrete composite (TCC) floors to make substantial contributions to CE. This work includes a comprehensive review of existing deconstructable connection systems applicable to TCC floors, shedding light on potential challenges associated with their implementation. Other innovative approach was proposed by Finch and Marriage [56], who demonstrated that timber structures can be designed in a manner that facilitates the direct and economically efficient reuse of materials. These authors proposed a digitally fabricated light structural frame that seamlessly integrates connection and assembly functions. Their work was supported by life cycle analyses and durability studies, suggesting that a reusable structural frame can be a practical and low-waste solution in building construction. Yan et al. [57] have created dismountable and panelized light-timber framed (LTF) construction systems, which open possibilities for adaptable building design through panels reuse.

Several authors have identified additional challenges for the development of DfD in timber construction. Ahn et al. [58] stressed the need for the development and harmonization of Design for Manufacturing, Assembly, and Deconstruction (DfMA + D) approaches tailored specifically for MT buildings, including innovative connection systems to facilitate assembly and disassembly. Materials passports during the design phase would encompass the entire lifecycle of construction materials, to simplify designing for reuse, disassembly, and material planning in case of deconstruction [51,59]. Developing disassembly-friendly connections is another critical aspect [47]. Further, motivations for deconstruction vary by country, influenced by location, site value, and recoverable timber availability [60]. Ghobadi and Sepasgozar [30] and Niu et al. [61] emphasized the importance of architects and designers considering deconstruction instead of demolition at a building's EoL, with potential MT reuse integrated into the original design. Minunno et al. [62] highlighted that non-standardized building measures hinder the application of the 3R's (Reduce, Reuse, Recycle) and circularity in building materials, suggesting the need to encourage the construction industry to design reusable components that can be easily disassembled and reused. Furthermore, Höglmeier et al. [63] noted that robust and efficient analytical sensor technologies are necessary to reliably identify impurities and contaminants and facilitate timber reuse. Sandberg et al. [29] suggested that minor design alterations in timber buildings can significantly enhance building details for deconstruction and reuse, emphasizing the importance of material tracking, environmental impact documentation, and mandatory deconstruction plans during the permitting stage for new buildings. Finally, a holistic design approach that encompasses technical aspects like materials, structure, and energy, as well as interior and furniture design is needed to fully apply CE principles [64].

The above-mentioned works represent significant steps toward more sustainable and environmentally friendly construction practices. However, more than twenty years after Crowther [35] set the basis for DfD, O'Grady et al. [65] demonstrated that demolition remains the favored method over deconstruction and disassembly. For Cristescu et al. [66], structural reuse of timber remains uncommon due to barriers such as low demand for salvaged materials, restrictive building regulations, and the absence of design standards. Modern timber construction currently lacks alignment with CE principles and often overlooks EoL considerations despite the potential of offsite construction to enhance precision, material efficiency, speed, and waste reduction in timber construction.

3.2.2. *Design for adaptability/adaption (DfA)*

The concept of Design for Adaptability/Adaptation (DfA) was described in Ref. [67] as “a strategy used to avoid building obsolescence, and the associated environmental and cost impacts of resource consumption and material waste”. DfA offers advantages for users, property owners, and society by allowing buildings to transform and adapt to different needs over time. It aligns with the idea that the most sustainable building is one that remains standing, or secondarily, one that can be efficiently deconstructed and reused [9,68]. DfA is an important step of the roadmap towards circular design solutions for timber buildings: the capacity of timber buildings to transform during their lifetime to accommodate different needs contributes to a lower carbon footprint [69]. DfA shares principles with DfD, as both concepts involve planning for a building's components disassembly at different stages of its lifespan [7,8]. Moreover, buildings considering DfD principles offer higher adaptability for future changes or repairs [53]. Strategies such as potential for future expansion, flexible layouts, modular components and simplified and standardized connections are crucial for enhancing building adaptability [30]. Likewise ease of disassembly and reuse is facilitated, requiring mechanical and reversible connections, prefabricated structures, load-bearing elements, non-load-bearing façade components, and independent building parts [30].

As it is difficult to implement DfA strategies in existing buildings which were not designed with this design philosophy in mind, the Buildings and Material Bank (BAMB) method [70] has emerged to avoid this problem. This involves creating a plan and developing design measures for adaptable buildings. The plan includes a rulebook with tools to measure waste production during the transformation of building façades. Lisco and Aulin [71] highlighted that the main features of Design for disassembly and adaptability (DfD/A) are the link between EoL and design phases by means of a deconstruction plan proposing a taxonomy to define relationships between various concepts, including DfD and DfA.

Numerous innovative design concepts have emerged to promote building adaptability and life cycle extension. In Ref. [72], these concepts emphasize reversibility, prefabrication, and recyclability, reducing waste generation as buildings reach their EoL. In this line, Klinge et al. [72] established that a fully reversible, prefabricated, multi-story residential building from waste wood reflects robust but flexible and adaptable solutions to extend the buildings-life cycle. Also, researchers have explored more adaptable solutions in timber structures with adaptable and scalable housing models [73], reuse-ready timber systems for modular buildings [74] and CLT panels as a product which can be adapted easily as use dictates [75].

The transition toward a CE involves adopting philosophies like DfDR and DfA. However, their widespread application is not yet common practice, and the literature on DfDR/A in timber buildings remains limited [76]. Nevertheless, designers can promote sustainability by designing MT buildings adaptable to several future scenarios. Therefore, adaptability or flexibility should be considered in the early project planning phase [51] and, to be applied a plan is needed [71].

Summarizing, timber, often considered a sustainable alternative to materials like concrete and steel, also plays a pivotal role in achieving adaptability in structures [16]. The focus on materials and components in the literature on circularity in timber architecture has gained prominence, with EWP offering sustainability potential within the conceptual architectural framework of adaptability [36].

3.2.3. Principles, indicators and guidelines for DfD/A in timber

To identify challenges and opportunities in DfD/A, it is essential to establish generic principles and guidelines applicable to any design. The understanding of these principles can be enhanced with comparative studies and critical reviews. Additionally, indicators should be developed to quantify the suitability for disassembly of a specific structure. These types of studies are summarized next.

Laasonen and Pajunen [33] conducted a study where they compared criteria and guidelines from various sources, including [45,57,77–80]. The criteria assessed included ease of access to components, ease of disassembly, independence, simplicity, and standardization. They concluded that the evaluation criteria for qualitative DfD assessment do not differ significantly from each other. In addition, Laasonen and Pajunen [33] also defined a set of factors influencing DfD, proposed an evaluation method and showed that the existing criteria for disassembly assessment are sufficient. A different conclusion was reached by Cristescu et al. [66], who condensed the principles and recommendations for DfDR previously put forth by various authors [12,78,81–84]. These authors concluded that, while a universal comprehensive indicator system encompassing deconstructability and reusability could be adopted, the primary indicators for DfDR, namely Time, Separability, Risk and Safety, Simplicity, and Interchangeability, are recognized as somewhat abstract. Alternatively, rather than employing a broad indicator system, a more pragmatic strategy involving individualized assessments of DfDR may be pursued. Finally, Kissi et al. [85] provided a critical review of DfD principles in the last twenty years identifying 22 principles for DfD and emphasizing the importance of documentation, component standardization, and mechanical joints. Table 1 summarizes the principles gathered in these publications [33,66,85].

Several additional tools and frameworks have been developed to evaluate and facilitate DfD and circularity in construction projects. Conejos et al. [86] developed the adaptSTAR model for assessing future adaptability in building designs. This novel design-rating tool was expected to empower designers to make informed choices, aiming for maximum efficiency and extended utility lifespan in their creations. In Ref. [48] a conceptual-knowledge model was developed for assessing disassembly capacity in buildings and systems defined by a single parameter function of the following factors: (1) material levels (type of material and components), (2) structure and (3) connections. Dams et al. [32] introduced the Circular Construction Evaluation Framework (CCEF), based on international design code guidelines to quantify the circularity of construction projects, including timber structures with DfD. Rakhstan et al. [87] developed a predictive model using machine learning to assess the economic reusability of load-bearing building elements, which can be relevant to timber structures with DfD. In this line, a design with reuse guide was created to promote circular design solutions [88]. Finally, Di Ruocco et al. [31] used two different assessment methods, the UNI 11277:2008 method and the integrated experimental method, to evaluate the disassembly capacity of two case studies with timber structure (single-family villa and a social housing complex) and demonstrated that all the technical elements scored higher when assessed with the integrated experimental method.

In relation to the ability to disassemble a timber structure, Building Information Modeling (BIM) constitutes a powerful tool, as several authors have highlighted. Akanbi et al. [89] introduced the Disassembly and Deconstruction Analytics System, which harnesses BIM's capabilities to offer design-centric and information-centric features. This system incorporates a conceptual-knowledge

Table 1
Key DfD drivers.

Laasonen and Pajunen (2023)	Cristescu et al. (2020)	Kissi et al. (2019)
Ease of access to components	Low weights and small sizes for easy dismantling	Documentation of materials and methods
Ease of disassembly	Accessibility of joints	Standardization of components
Independence	Separability of subcomponents for easy dismantling	Use mechanical joints instead of chemical joints
Simplicity	Low susceptibility against damage during disassembly	
Standardization	Repetitiveness	
	Similarity	
	Standardization level	
	Low exposure to deterioration processes	
	Expected long-term deformations are not significant	
	Transportability	
	Documentation about design and maintenance	

model aimed at assessing the disassembly potential of buildings and systems. Sandin and Sandberg [90] conducted a study focused on optimizing design processes to facilitate deconstruction and subsequent reuse introducing a metric called the "rebuilding factor" to evaluate the potential for deconstruction and further/later reuse in building designs. Moreover, for enabling the reuse and adaptation of buildings, it is essential to foster the development of new materials and construction concepts. Additionally, contemporary planning processes for timber structures should consider the potential for disassembly and subsequent reuse. The growing digitalization and increasing adoption of BIM programs hold the promise of revolutionizing the deconstruction of timber buildings in the future [72].

In addition, Sandin et al. [39] highlighted the alignment of ISO 20887 [77] principles with DfD/A design examples, acknowledging the standard's generality and abstraction in representing diverse building and civil timber engineering projects. Sandberg et al. [29] explored essential documentation for a Deconstruction Plan, drawing on literature sources to outline strategic statements and inventories. These sources encompassed: (1) a strategic statement outlining deconstruction and reuse approaches; (2) an inventory of building elements accompanied by warranties, service life, and potential for reuse; (3) step-by-step disassembly instructions featuring plans, necessary equipment, and dismantling methods; and (4) a coherent proposal for document retention. Psilovikos [41] emphasized the need to revise European building codes to accommodate timber in deconstruction projects and reusability.

Finally, an important step forward towards the implementation of DfD/A was the legislation introduced in the United Kingdom in the field of construction, although it is not limited to wooden structures [91]. They published a comprehensive document that categorized Modern Methods of Construction (MMC) into seven distinct categories. These MMC categories incorporated prefabricated 3D primary structural systems, such as volumetric units (i.e. 3D modular elements like prefabricated houses), prefabricated 2D primary structural systems like panels, and prefabricated linear structural components including beams and columns. Additionally, the document encompassed prefabricated non-structural assemblies like kitchen and bathroom units, outlining the government's commitment to regulating and promoting these emerging construction methods [91].

Collectively, these tools, reviews, and approaches contribute to the advancement of DfD/A and circularity principles in timber construction projects, providing valuable insights and practical methods for implementation while highlighting the need to continue advancing in the standardization of these concepts.

3.2.4. Prefabricated technology

The term "prefabricated construction", as opposed to "site-built" construction, refers to a construction process where large portions of a building are manufactured off-site in a factory environment and later transported to site for assembly. Prefabricated systems can be classified into different categories, depending on the extent of building product completion in the factory environment such as panelized, sub-assemblies, hybrid or volumetric systems [92]. Prefabricated wood building kits are made up of prefabricated components delivered and assembled on site. This typically involves the use of prefabricated panels that can create complete sections of a building, including roofing components, structural elements (ceilings, decks, and beams), building framework (wall panels, beams, columns, and shear panels), and even integrated glazing packages (walls with pre-installed carpentries). As showed in Ref. [29], modular and prefabricated timber construction, consistent with the principles of ISO 20887 [77], reduces construction waste, improves quality due to factory controls, reduces on site assembly time, and results in fewer unplanned connections that can undermine the deconstruction process. This can be enhanced for adaptability by limiting the number and complexity of the panels to improve reuse/replacement potential; centralizing spatial and structural layouts to allow for flexibility, adaptability, and expandability; and centralizing the service runs for maintenance. Prefabricated assemblies show good promise for deconstruction based on reusing the panels ([29].

Prefabricated components have been highlighted as one of the principles of DfD [28,31,85]. Similarly, mechanical connections or prefabricated members ensure disassembly to obtain reusable components without damage [38,93,94]. Kuiri and Leardini [73] demonstrated that the advancements in prefabricated timber technology enable to enhance DfA by allowing housing to expand or reduce in size according to evolving household requirements and preferences. Ghobadi and Sepasgozar [30] proposed various prefabrication design strategies to facilitate timber component disassembly and reuse. Godina et al. [95] explored the potential of modularity, prefabrication and design methods of demountable timber products as opportunities that could be utilized to unlock the potential of upcycled secondary elements while Lisco and Aulin [71] showed that through modularization and prefabrication, and by means of DfD/A using specific connectors, each part of a timber building has a high potential for reuse. A recent study showed that in timber-based buildings, 65 % of materials are reusable and 35 % are recyclable [96].

Jockwer et al. [69] underscored the importance of prefabrication and modularization as mainstream practices in the pursuit of DfA, highlighting its pivotal role in advancing this critical architectural paradigm. In the evolving landscape of timber buildings, a prominent trend is the increasing reliance on prefabrication and volumetric modules, which pose challenges to the conventional notions of adaptability [36]. Building upon this trend analysis, Piccardo and Hughes [45] identified distinct patterns within contemporary architectural practices. This research unveiled three prominent patterns for upstream strategies, encompassing the reversibility of joints, autonomy of different components, and the integration of prefabrication.

Sustainability and circularity in prefabrication practices has gained significant attention in recent studies. Ahn et al. [58] emphasized that MT possesses inherent characteristics such as the prefabrication of panelized assemblies and renewable material properties, aligning well with CE principles. This observation is further reinforced in Ref. [98], which underscored the potential for reducing GHG and minimizing waste generation by implementing low-embodied carbon prefabricated modular systems, integrating solid wood panel construction, and embracing DfD principles. In this line, Lehmann et al. [75] highlighted the benefits of zero waste construction systems focusing on construction waste avoidance, leading to the development of low-carbon-lifecycle building components suitable for urban housing. Akanbi et al. [89] recognized the significance of prefabrication in the context of building design, particularly concerning EoL considerations. Looking ahead, MT buildings designed with large-size prefabricated elements and reversible mechanical connections, hold considerable potential for post EoL options, including recycling and reuse [34]. Minunno et al. [62] showed the environmental advantages of a prototype timber modular building with DfDR, both in terms of GHG reduction and other environmental indicators.

Furthermore, Lehmann [46] emphasized the importance of using sustainable materials and prefabricated systems to ensure affordability in environmentally driven projects. This was exemplified through the exploration of prototype designs for large-scale prefabricated timber elements, with the aim of enhancing the construction process and the energy efficiency of building envelopes, along with modular design principles facilitating transformation and disassembly. Lastly, Juaristi et al. [54] showcased the potential of highly prefabricated manufacturing processes in timber-based façade technologies to effectively reduce the carbon footprint, minimize water use and reduce waste generation. Additionally, the avoidance of glued parts emerged as a strategy to enhance the sustainability of façades by enabling the replacement of individual elements.

Several studies have explored innovative approaches to construction connections and their implications in timber prefabrication. Laasonen and Pajunen [33] highlighted the widespread adoption of highly prefabricated joints, known as plug-in joints. In a related context, the achievement of efficient building processes through the utilization of prefabricated timber members with embedded connector elements, such as glued-in rods or self-tapping screws, has been discussed, demonstrating the potential of these methods in structural applications [69]. Moreover, Adel et al. [99] ventured into the realm of robotics for prefabrication and spatial assembly of timber frame structures at the building scale, underlining the importance of adhering to additional constraints such as modularization and programmatic organization. Additionally, Derikvand and Fink [100] introduced a concept for a deconstructable connector utilizing self-tapping screws, designed for both prefabrication and cast-in-situ construction of TCC floors. Meanwhile, Shulman and Loss [101] advocated for other deconstructable hybrid connections, particularly conducive to off-site prefabrication and on-site disassembly, presenting a valuable approach to enhance construction flexibility. Importantly, within the domain of prefabricated timber construction, it has been observed that employing prefabricated timber elements reduces reliance on chemical connections [102]. Instead, mechanical joints are favored due to their ease of disassembly, which facilitates the construction process and allows structures to remain intact and reusable, aligning with sustainable construction practices.

In the pursuit of innovative structural solutions, Zanni et al. [103] introduced a unique approach involving the adoption of a timber shell composed of CLT prefabricated panels. These panels are skillfully connected to both the building and its foundations using dry, standardized, and easily demountable connections with earthquake resistance capabilities. A related exploration [104] delves into timber space-frames, which were purposefully designed to provide complete modulation of a building's structure using lightweight and discontinuous members. Moreover, Androsevic et al. [70] unveiled a prototype for a reversible timber façade, intended to offer significant reuse potential. While already promising, this concept holds room for further improvement and refinement, with components being clustered into prefabricated independent elements. In parallel, Finch and Marriage [56] developed a prefabricated and modular timber frame construction solution. This innovative approach prioritizes material reuse to effectively curtail waste production. Finally, in a notable experiment, Derikvand and Fink [55] explored the flexibility and adaptability of a deconstructable connector designed for reuse, contributing valuable insights into structural resilience and sustainability.

Despite the important advances, timber prefabrication also faces major challenges. The potential of multistorey timber construction remains partially unexploited in Europe despite Europe's large forest cover and the existence of a well-developed prefabricated timber building industry in many European countries [105]. Off-site prefabrication offers the advantage of a controlled and predictable fabrication environment, leading to high precision and overall building quality. However, it may be less efficient for transportation when compared to on-site fabrication [106]. Additionally, automation poses a significant challenge in finding efficient robotic processes that can seamlessly integrate all functional requirements, including thermal insulation, airtightness, and technical systems within a continuous fabrication framework. Finally, regional variations in prefabrication levels, material choices, and designs require the adaptation of DfDR design guidelines to the local context [66].

3.2.5. Construction methods and structural analysis

The studies also explore construction methods and structural analysis, investigate structural concepts in wood construction, cover the various phases of timber construction, and include illustrative diagrams and images. Furthermore, a wide range of material connections and designs, such as wood-wood, wood-concrete, and wood-metal, are thoroughly analyzed, along with a diverse set of construction details.

Making progress on the issue, Shulman and Loss [101] focused on connections that employed partially threaded 20M and 24M steel rods embedded within pockets created within CLT and encased by thick crowns of high-strength three-component epoxy-based grout. The findings laid the foundation for the formulation of mechanics-based design models and formulae, akin to those commonly applied for conventional dowel-type fastener timber connections. Tanadini et al. [107] unveiled the CantiBox, a pavilion composed of linear timber elements assembled robotically and delved into the load-bearing and displacement behavior of steel-timber composite beams, with a particular emphasis on the shear connection between steel and timber. In a related development, Romero et al. [108] have presented demountable timber connectors and the results of push-out tests. Their paper not only outlines the tested mechanical properties of Laminated Venner lumber (LVL) but also provides insights into the push-out test setup and procedure. Also, other innovations [109] include a 3D printed bio-composite removable connection system for bamboo space structures. This connection system was employed in a pyramidal structure made of bamboo culms of 30 mm of diameter and 4 mm in thickness able to sustain a compression load of 7 kN demonstrating the relevance of the innovative connection system [109]. Finally, circular design influences materials, cross-sections, and connections in bending-active structures [110]. The interlocking connections, their reversibility, and the ability to vary the structural system offer the promise of a longer service life for load-bearing structures.

Regarding structural joints, Riggio et al. [111] observed variability in timber-to-timber joints, within parameters like slippage modulus and maximum load, which was primarily attributed to geometric flaws that occurred during nail insertion. Pongiglione et al. [112] introduced a novel steel connection designed for seismic applications and full disassembly in a reversible manner, ensuring the complete reusability of structural elements, which could be also applicable to design timber structures according to DfD principles. Yan et al. [57] presented an innovative approach by employing reversible MT connectors for LTF construction. The study compared its own strength prediction models against the European Technical Assessments (ETAs) formulae. The former model demonstrated superior accuracy. Lie and Tsalkatidis [113] explored the relationship between rotational stiffness in beam-to-column connections and structural reusability. They found that higher rotational stiffness shifted the building's first torsional mode to a higher mode and lower frequency but generally decreased the reusability of structural components. However, they revealed that it’s possible to balance design for seismic loadings in low seismicity regions with designing for future reuse by selecting beam-to-column connections with appropriate characteristics. In a large-scale test, Smith et al. [52] evaluated a structural form consisting of post-tensioned timber frames, walls for lateral and gravity resistance, and TCC floors. Their findings showcased the ability of post-tensioned timber to withstand high levels of drift with minimal to no structural damage. Furthermore, the tested structural form displayed full recentering characteristics with no residual displacements, which is a significant contributor to post-earthquake cost savings.

In their investigation of Cross Secondary Laminated Timber (CSLT), which is the recyclability concept of reusing secondary timber as feedstock for CLT, Rose et al. [114] conducted small-scale laboratory experiments to assess the fabrication process and mechanical properties of CSLT. The outcomes revealed no significant distinctions in compression stiffness and strength between CLST and a control CLT. Moreover, the application of finite element modeling shed light on the impact of typical minor defects on CLST panel compression stiffness. However, it became evident that the use of secondary timber significantly affects bending stiffness. To address this, the authors proposed an effective combination of primary and secondary timber and identified their appropriate structural applications.

In the realm of innovative timber systems, Estrella et al. [74] introduced the Pixel Slab system formed by a horizontal grid-like slab supported by timber columns. Slab elements are made up of GLT beams orthogonally connected and can span up to 6 m. Beams are manufactured by gluing eight timber laths with alternating discontinuities. It is a pioneering load-bearing timber system meticulously designed for deconstruction and reuse across multiple building lifespans. Hansen et al. [115] have unveiled an innovative form of connection, seamlessly producible using conventional Computer Numeric Control (CNC) procedures, which enables the assembly and disassembly of timber elements through robotics and demonstrated that the incorporation of semi-spherical shear keys significantly enhances shear capacity and connection stiffness.

Reversible connections are a key component of DfD timber structures, as demonstrated by studies conducted by Pozzi [79] and Ottenhaus et al. [68]. Pozzi [79] illustrated timber connection systems that offer the best compromise between maximizing disassembly and reuse potential while also optimizing the structural performance and in-use quality of engineered wooden structures. Ottenhaus et al. [68] investigated types of connections that can be disassembled and reused, providing the following recommendations:

- Connections should generally remain in the elastic domain.
- Capacity design and the use of potential ductile elements designed for replacement (fuses) to facilitate energy dissipation is recommended. Elements like hyperelastic rubber hold-downs, U-shaped flexural plates (UFPs) and resilient slip friction joints can be employed as dissipators.
- Permanent deformations should be concentrated in replaceable steel elements rather than in timber elements.
- Typical fasteners such as nails, dowels, or screws show only a limited potential for DfD, while proprietary brackets can potentially achieve reversibility for their intended application.

Additionally, Ottenhaus et al. [68] underscore the importance of considering friction, creep, and durability issues such as corrosion in the initial design for disassembly. They identify major challenges in the field, including: 1) the impact of reverse-cyclic, repeated, and alternating loading, 2) the impact of combined (axial and lateral) loading on reversibility, 3) moisture effects, 4) performance after repeated disassembly and reassembly, and 5) residual capacity of reclaimed timber elements. Furthermore, Ottenhaus et al. [68] also presented interesting examples from the DfD perspective, such as:

- Post-tensioned structures such as those referenced by Brown [116] are usually combined with dissipative PDE hold-downs (e.g., threaded-rod type dissipators, RSF hold-downs, or hyper elastic rubber dampers).
- Structures using elastic assemblies like the XPAN/Quick Connect system [117–121].
- Structures like the Cradle Building in Düsseldorf, Germany, which have either been deconstructed or designed with DfD in mind.

Finally, Ottenhaus et al. [68] emphasize that despite several examples of built structures with reversible timber assemblies, more established building concepts with standardized timber components are necessary to fully benefit from the potential of disassembly and reuse.

3.2.6. Examples of projects and use programs

This section examines eighty (80) timber projects from fifty-four (54) different publications that applied the DfD philosophy or incorporated some of its principles, such as prefabrication, modular components, or reversible connectors. These projects have been categorized into five main groups: (1) residential, (2) office, (3) commercial, (4) public and social and (5) others. The public and social category encompasses diverse programs like educational buildings, pavilions or gangways. Fig. 6 reveals that most projects, constituting 66 % (53 buildings), fall within the residential domain. The office program follows at a considerable distance, comprising

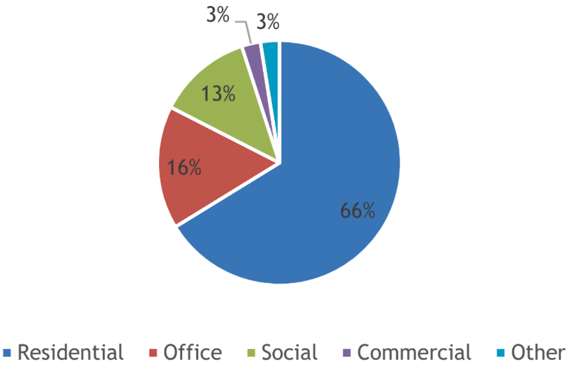

Fig. 6. Program.

16 % (13 buildings), while offices make up 13 % (10 buildings). Commercial use is represented by 3 % (2 buildings), and other purposes constitute 3 % (2 buildings, specifically a cow housing and factory), both in a marginal capacity.

Moreover, residential projects have been categorized according to the number of stories: less than 4 stories, 4-8 stories, or more than 8 stories. As illustrated in Fig. 7, it is apparent that the majority of the projects, constituting 60 % (47 projects), fall into the category of buildings with 4 floors or fewer. In close succession, buildings with 5–8 levels represent 29 % (23 projects), while there is a limited presence of buildings exceeding 8 stories, accounting for 10 % (8 projects).

Svatoš-Ražnjević [122] classified 350 multi-storey timber projects from 2000 to 2021, mostly from Europe and USA, according to their program and without considering DfD. Their results are compared with the findings of the present study in Table 2. Both studies differ in program categorization and analysis but underscore the prevalence of residential programs and mid-rise timber structures.

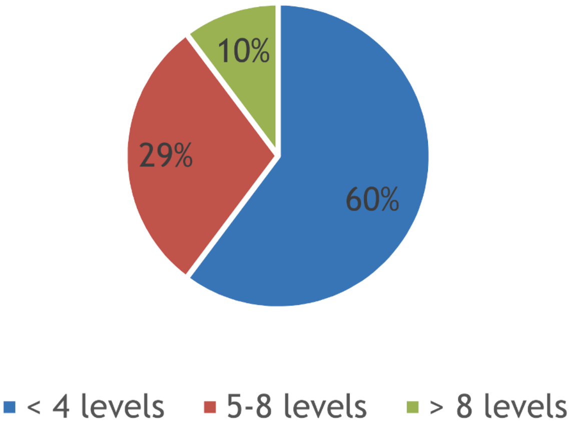

Fig. 7. Levels of residential program.

Table 2
Comparation between [116] and present paper analyses.

Element	Svatoš-Ražnjević (2022)	Present paper
Publication subject	Multi-story timber projects	Timber projects with DfD
Timeline	2000–2021	2000–2023
Number of projects	350	80
Location	Mostly in Europe and USA	Mostly in Europe
Program types	**(1)** residential and housing (46 %, 164 projects) **(2)** commercial, which includes offices (31 %, 109 projects) **(3)** mixed-use (13 %, 41 projects) **(4)** public and civic (10 %, 35 projects)	**(1)** residential (66 %, 53 projects) **(2)** offices, (16 %, 13 projects) **(3)** social (13 %, 10 projects) **(4)** commercial (3 %, 2 projects) **(5)** other (3 %, 2 projects)
Building height	**(1)** 5-7 stories (45 %) **(2)** <5 stories (29 %) **(3)** >7 stories (27 %)	**(1)** <5 stories (60 %, 47 projects) **(2)** 5-8 stories (29 %, 23 projects) **(3)** >8 stories (10 %, 8 projects)

3.2.7. Environmental aspects

Several research findings shed light on sustainability and environmental impact in DfD timber construction. Holistic approaches are vital to reduce carbon emissions in multi-story residential buildings, including material choices, construction typologies and DfD [123].

Demonstrating the effectiveness of circularity and reuse strategies, Dams et al. [32] highlighted the value of combining reused durable materials with modular, demountable, and adaptable design approaches in construction projects to improve circularity in construction sector. The potential for future developments in design categories within the CCEF is exposed, emphasizing the adaptability of these strategies over long-time scales. Additionally, Niu et al. [61] estimated significant reductions in the environmental burden through the reuse of structural wood components, particularly when considering wood as carbon-neutral. Expanding on the circular qualities of construction materials, Campbell [123] advocated for broader utilization of the Cradle-to-Cradle (C2C) certification process, emphasizing its ability to clarify both initial and EoL characteristics. This approach can facilitate the interchange of biological and technical materials, known as “cycle switching”, while maintaining consistency with circular processes. Furthermore, Kim and Kim [38] emphasized the potential benefits of deconstruction options and designs, including substantial reductions in CO_2 emissions and costs, up to 40.1 % and 1.3 %, respectively, when compared to initial designs with more difficult disassembly. These authors also underscored the role of reuse in mitigating emissions and cost increases associated with various deconstruction options.

In terms of environmental performance of MT with DfD, Kayaçetin et al. [124] highlighted the enhanced environmental performance of bio-based design principles due to the reduced environmental impact achieved through reuse and recycling in EoL scenarios. Kayaçetin et al. [124] introduced a novel approach that integrates circularity calculations with Life Cycle Assessment (LCA) methodology to provide more precise long-term impact analysis for circular buildings. Additionally, Gallego-Schmid et al. [125] emphasized the research focus on resource solutions aimed at reducing GHG. These solutions could potentially lead to remarkable savings of up to 99 % in GHG emissions per functional unit. Material reuse has demonstrated the ability to lower emissions by 30–50 % per functional unit, depending on factors such as recycling efficiencies and transportation distances to recovery facilities. In a related study, Minunno et al. [62] conducted a comprehensive environmental assessment of a purpose-built modular timber building with DfDR. These authors compared their LCA results with those of a contemporary construction approach focusing on material recyclability. The findings revealed that designing and constructing components for reuse, as opposed to recycling, can offset GHG emissions by an impressive 88 %. Additionally, this approach yielded positive results in several other tested environmental indicators, underlining its sustainability benefits. Furthermore, Di Ruocco et al. [31] introduced a method to evaluate the environmental impact of the disassembly and selective demolition process, aiming to identify the process with the lowest CO_2 emissions to minimize waste during the EoL phase. This methodology was applied to two wooden architectures, whose organic materials have the capacity to store CO_2.

Exploring alternative construction methods, D'Amico et al. [126] conducted research on the utilization of CLT as a substitute for concrete floors within steel structural systems. Their findings demonstrated substantial GHG savings, ranging from 20 to 80 Mt CO_2e (95 % confidence interval), with an average reduction of approximately 50 Mt CO_2. Similarly, Finch and Marriage [56] emphasized the significance of geometric and assembly conditions in achieving sustainable outcomes. The design proposed by these authors yield a remarkable 70 % reduction in embodied energy over the product extended lifetime when compared to conventional light timber platform framing, underlining its potential to contribute to more sustainable construction practices.

These research findings collectively underscore the significance of sustainability, circularity, and environmentally conscious practices in construction, highlighting the environmental benefits of structural timber and DfD.

3.2.8. Durability

Reuse of timber components has further requirements regarding ensuring durability, limited wear and tear, and reliable assessment of the remaining service life due to the duration of the previous loads carried by the timber components. Durable design is defined as long-lasting components with adequate tolerances to withstand repeated dis- and re-assembly and reuse, thereby lasting several building lifecycles [127]. Vandamme and Rinke [36] underscored the significance of designing timber structures with longevity in mind and revealed that, paradoxically, over half of all buildings face demolition not due to technical deficiencies but rather because of vacancy issues, suggesting an inadequate potential for adaptation. Additionally, circularity strategies such as design for durability and repairability can complement this approach.

MT elements can be degraded by many of the same organisms as solid wood [128]. The most common wood-degrading organisms are fungi, termites, postharvest beetles, and powder post beetles. Some moisture intrusion will be necessary for attack by most of these organisms. The successful use of MT requires crafting systems that minimize the risk of moisture intrusion and accumulation. These systems include moisture protection in transit and during erection, careful design to create water-shedding surfaces, proper installation of mechanicals ventilation systems to avoid moisture accumulation, proper use of membranes and other water-shedding devices, the use of more durable wood materials where appropriate, and regular maintenance to ensure that all the elements continue to perform as expected [128]. Ayanleye et al. [129] discussed traditional wood protection methods, including preservative treatment and thermal and chemical modification, and explored their potential application to protect MT assessing their impact on properties like wettability, glue penetration, and bonding strength. Ayanleye et al. [129] also reviews recent research on assessing MT durability and protecting MT structures by controlling moisture, while considering future developments in the field.

Several studies have explored technical approaches to improve durability of DfD timber structures. Circular construction thrives when it incorporates accessible mechanical connections and adopts a manufacturing-style approach, emphasizing the importance of durable and reusable standardized components and materials [32]. In line with this perspective, Riggio et al. [111] highlighted the concept of the densification technique (that, as showed Cabral et al. [130], is essentially an increase of quality and density of timber by decreasing the voids in the material through different techniques), which has been used to obtain a wood-based material with higher mechanical performance with respect to natural wood, offering also heightened durability and dimensional stability. In their study, Riggio et al. [111] utilized densified wooden nails for new timber assemblies and restoration works. Klinge et al. [126] further emphasized the role of high-quality materials in boosting both component and building durability, thereby extending their lifespan. Similarly, Piccardo and Hughes [45] advocated for high-quality self-drilling screws as a means to bolster the durability and reversibility of joints. Moreover, simultaneous application of upstream and downstream strategies was suggested to ensure building durability and streamline the disassembly and reuse of wood elements.

Lehmann and Kremer [98] emphasized the importance of designing for longevity and durability. Their approach included weather protection, specialized treatments, mitigating water ingress risks, and preventing trapped moisture within ventilated wood structures. Sandberg et al. [29] underscored how employing durable, long-lasting materials, such as MT or heavy timber, or replacing engineered joists with solid timber elements like OSB, can facilitate reuse cycles, aligning with the broader goal of promoting sustainability in construction.

Durability and DfD are interlinked aspects that play a crucial role in the circularity of construction practices. Laasonen and Pajunen [33] underscored the pivotal role of durability as a prerequisite for disassembly. A structure plagued by faults cannot be entirely reused, making it imperative to comprehend how durability and life cycle design impact the potential for reusing disassembled components. To ensure the safety and healthiness of a structure post-disassembly, approval and suitability for the intended use of a reusable structure are vital. This necessitates the establishment of standardized methods within the construction industry to facilitate reuse [33]. Ahn et al. [58] further emphasized the integration of durability into design concepts. They noted that while design concepts like DfMA and DfR emphasize deconstructability and reusability, they may not inherently encompass durability and maintenance considerations. This gap is especially pertinent when applying CE assessment indicators to MT buildings. Campbell [123] highlighted the need for a clear focus on the design and detailing of MT buildings to enhance their durability and effectively manage material stocks.

Kibert and Languell [132] emphasized the importance of selecting structures and elements capable of withstanding the changes that occur between their initial construction and subsequent use. Factors such as durability, strength, adherence to standards, and even social and fashion trends are relevant in this context. When buildings contain valuable materials, it becomes essential to ensure their accessibility for reuse after the building has fulfilled its initial service life. Therefore, DfD is a key element in material retrievability. Considering material aspects, durability, desirability, and longevity are integral considerations. Materials must possess the necessary durability to withstand multiple service lives. Achieving a balance between durability and adaptability is pivotal, as longevity hinges on both the durability of materials and the adaptability of the building to evolving needs. Balancing these factors effectively is essential in promoting circular construction practices.

In terms of circularity, Gallego-Schmid et al. [125] considered durability as one of the key strategies to achieve circularity in the construction sector while Lebossé et al. [133] claimed that reuse of reclaimed timber is not guaranteed by the reversibility and appropriability of the wood material. The continuity of its original use is in direct competition with recycling and energy recovery.

Finally, Sandin et al. [76] showed that using solid wood components instead of engineered wood products (as glulam, CLT or LVL) are a means to achieve durability. In this line, Pongiglione and Calderini [112] developed a novel reversible seismic-resistant joint for steel structures, which can be applied to timber structures. These authors have done a sustainable structural design according to strategies such as durability, adaptability, and reusability. The problem of durability might not be the actual service life of components, but the uncertainty around it or the manufacturer's warranties. Real data on long-term performance of different materials and negotiations for extended warranties might expand the life span of some components. Sandin et al. [76] showed that timber components will still need to be verified before they can be reused, and it is necessary to test and verify whether reclaimed elements still show sufficient properties for reuse. Durability can also be achieved by protecting timber from adverse conditions. The deconstruction of a traditional farm building in Spain showed that, in the stable buildings, better-protected timber members in the dwelling house could be recovered in a better condition than less protected elements [76].

In short, designing timber structures with longevity in mind is crucial, given that many buildings are demolished due to vacancy rather than technical issues, which emphasizes the need for adaptability and circularity strategies such as durability and repairability. Technical approaches, like innovative materials and comprehensive designs, bolster durability in timber structures meant for disassembly, ensuring their suitability for future use and advancing circular construction practices.

3.2.9. *Testing and structural monitoring*

In recent years, the potential for reusing timber from dismantled structures has garnered significant attention in research [134]. However, the vast promise of reclaimed wood in construction faces a challenge due to grading and testing standards lagging behind evolving technology and practices in the realm of reclaimed timber. To overcome this hurdle, there is a pressing need for a specialized standardized framework [134]. Reclaimed timber introduces a level of mechanical properties variability that exceeds that of new timber, emphasizing the importance of a comprehensive analysis of its impact on stress grading and determination of its characteristic mechanical property values [134].

To ascertain the practical viability of reclaimed timber, Brol et al. [135] conducted extensive testing on timber structural members extracted from dismantled structures and underscored the suitability of these elements for reuse. Notably, reclaimed timber exhibits dimensional stability over time, often boasting larger cross-sections than contemporary wood. However, it is essential to acknowledge the associated challenges. The presence of cracks, ruptures, fastener holes, cutouts, notches, and the prevalence of biological degradation, particularly at the ends of elements and traces of insect activity, pose limitations to reusability. Detecting and addressing defects is achievable through preliminary macroscopic assessment, in situ Non-Destructive Testing (NDT), and laboratory tests, facilitating an estimation of structural parameters and ensuring compliance with design and construction requirements [135–137]. Furthermore, the study by Sandberg et al. [29] reinforces the applicability of reclaimed timber, particularly recovered softwood and hardwoods, in structural applications. Their research underscores the mechanical performance of MT products crafted from reclaimed wood is on par with those made from new timber, further advocating for its suitability in construction projects.

When evaluating aged timber for reuse in construction, several critical factors come into play [131]. These factors encompass preservation status of the timber, damages incurred during dismantling, and the prior loading conditions all play significant roles. Extensive research spanning back to the 1950s has established that the effects of aging can be effectively managed when meticulous assessments of preservation status and other variables are conducted [138].

One approach to enhance the usability of salvaged timber involves the use of standardized cross sections. This not only aids in avoiding storage costs but also contributes to increase market acceptance of reclaimed timber. Additionally, the utilization of finger joints presents an attractive avenue for recycling construction and demolition waste (CDW) timber which can be used after remanufacturing. This technique allows defects to be removed, and shorter salvaged timber pieces can be finger jointed together to create continuous lamellae of the required length [138]. Modern advancements in visual strength grading have introduced machine-assisted methods that can significantly enhance the assessment of mechanical properties, especially in higher strength classes. These technologies encompass various techniques, including flexural resonant frequency, x-ray measurements, and ultrasonic wave speed measurements. Addressing the issue of recovered wood properties, there is a growing need for rapid on-site testing solutions to mitigate the cost and time associated with traditional sampling and laboratory analysis. The Frauenhofer Institute has pioneered the development of an on-site measurement prototype device, potentially revolutionizing wood classification practices at demolition sites [138].

In the realm of timber structural testing and evaluation, several notable studies and methodologies have emerged. Kim and Kim [38] have advocated for the application of NDT such as visual inspection, ground penetrating radar, and digital radioscopy [111]. These techniques provide valuable insights into the structural integrity of various materials and components. Furthermore, Rakhshan et al. [87] developed an economic model to predict the reusability of structural elements at a building's EoL. Although this model is not exclusive for timber buildings it offers a proactive approach to sustainability. Cavalli et al. [138] have contributed to this field by formulating a linear regression model that utilizes NDT outcomes to forecast the mechanical characteristics of timber sections, both in service and reclaimed.

Smith [139] has significantly advanced the feasibility of reclaiming timber joists from demolition operations. His work introduces a cost-efficient methodology for visual grading, which can be readily implemented on site. This methodology enhances the reuse potential of timber elements salvaged from demolition activities. Ahn et al. [58] have ventured into the realm of salvaged/recycled lumber, manufacturing and testing CLT panels to characterize their mechanical properties. While most panels successfully met examination criteria, some challenges related to delamination requirements were encountered, suggesting the need for further research and scale-up testing [140]. Additionally, Derikvand and Fink [100] have demonstrated similar shear behavior between deconstructable connectors and permanent connectors, albeit with marginally lower strength and stiffness properties.

A comprehensive understanding of reclaimed timber's mechanical properties has been explored by Falk et al. [141]. Their study of small clear wood samples showed no significant difference in strength, modulus of elasticity or mean bending strength in comparison to new wood. Tests on full-size flexural members showed a reduction in mean bending strength of about 25 % in comparison to equivalent new timber. Moreover, Crews and Mazkenzie [142] have concluded that existing visual grading rules (AS 2082) can be effectively applied to assign properties for timber cut from larger members, provided they do not contain defects such as degradation and bolt holes. Furthermore, Smith [139] introduced an alternative investigation method aimed at estimating the modulus of elasticity of recovered wood, specifically tailored for operatives at demolition sites, employing simple measuring equipment. Arbelaez [140] has delved into the realm of non-destructive evaluation (NDE), emphasizing its significance. His research demonstrates that 96 % of salvaged lumber provided by Portland deconstruction contractors subjected to NDE were sufficiently stiff to meet the minimum requirements for manufacturing CLT panels. This underscores its suitability for CLT production, even when considering defects. Furthermore, Smith [139] introduced an alternative investigation method aimed at estimating the modulus of elasticity of recovered wood, specifically tailored for operatives at demolition sites, employing simple measuring equipment.

While the use of MT is a promising structural choice, Schimleck et al. [143] highlighted the existing challenge of limited wood properties data from deconstructed residences and revealed that a significant portion of the samples analyzed exhibited stiffness levels comparable to the highest structural design grade for Coastal Douglas-fir lumber. Despite the presence of knots and damages, 96 % of the samples met the manufacturing requirement of CLT with E3 grading.

Monitoring technologies and strategies can play a pivotal role in ensuring the longevity and structural integrity of buildings. Lehmann and Kremer [98] have underscored the importance of research in this domain, emphasizing the need to investigate the long-term efficacy of moisture monitoring devices. They propose the installation of a network of sensors on waterproof membranes to continuously monitor moisture content trends and facilitate timely repairs as needed. Additionally, they advocate for targeted structural monitoring through strategically placed sensors, facilitating ongoing structural health monitoring. This structural monitoring approach can be effectively synchronized with the treatment of lamella feedstock used in the production of MT products, particularly in areas prone to moisture exposure. This integration ensures that structural components are adequately prepared for wet environments, thereby enhancing their durability and performance. In a related development, Zanny et al. [103] have introduced an innovative structural system that incorporates a CLT prefabricated exoskeleton and integrates advanced sensor technology. These sensors serve a dual purpose by guaranteeing the comfort of building occupants and optimizing energy consumption. Furthermore, they play a vital role in the continuous monitoring of the building's structural health, ensuring its long-term stability and safety.

According to Finch and Marriage [56], certification plays a pivotal role in the promotion and widespread adoption of material reuse within the timber industry. These authors propose a set of practices designed to facilitate post-use certification and strength testing of recycled materials, which is essential for ensuring the integrity and reliability of reused construction materials. Among these practices, visual strength grading of recycled timber stands out as a critical factor. This approach empowers the construction industry to not only embrace the reuse of timber materials but also to make it a cost-effective and accessible option for a broader range of projects. Additionally, addressing the challenge of wood preservatives is crucial in the context of certification and material reuse. The conventional approach involving sampling and subsequent laboratory analysis is both costly and time-consuming. As highlighted by Klinge et al. [131], there is a growing need for the development of rapid on-site testing methods. Such methods would offer a more efficient and practical means of assessing the suitability of reclaimed timber, further supporting the certification and successful integration of recycled materials into construction projects.

Finally, due to damage accumulation, during the building's usage phase and its dismantling or demolition, the strength properties of reclaimed timber elements can be lower than those of new timber elements. Several standards, recommendations and studies face the challenge of grading reclaimed timber or timber from old buildings. Some of them are:

- The Australian industry interim standard for recycled timber [144], which provides guidance on the grading of recycled hardwood timber, including rules for design and for defining timber mechanical properties.
- The Italian standard UNI 11119 [145] on the on-site inspections for the diagnosis of timber members.
- The European standard EN 17121 [146]. Which contains guidelines for the on-site assessment of load-bearing timber structures.
- Studies combining visual grading, non-destructive assessment and bending tests like those by Arriaga et al. [147] and Kauniste et al. [148].

Summarizing, the bibliographic search has shown that although wood recovered from dismantled or recycled structures can be valid for reuse, greater progress is necessary in terms of grading standardization and subsequent structural analysis methods, development of rapid on-site analysis, use of structural monitoring and on balance, certification schemes of reclaimed/reused wood elements.

4. Discussion

4.1. Discussion of the results

The extensive body of research presented in the collected studies underscores the paramount importance of adopting circular construction principles, particularly those centered on DfD/A in the contemporary construction industry. These principles emphasize the ability to dismantle, reuse or rearrange building elements and connecting components, thereby curbing waste production and reducing GHG emissions. Research delves into various DfD/A aspects, providing insights into how it can be incorporated into modern timber construction practices.

Timber's natural properties, such as modularity and renewability, align well with DfD principles, making it an ideal choice for structures designed for future disassembly and material reuse in mind. However, the research has acknowledged the existing challenges, including labor-intensive disassembly processes, regulatory hurdles and the lack of demand for salvaged materials. Innovative connection systems are proposed to facilitate efficient disassembly and minimize material damage. The standardization, documentation of materials, and a shift towards non-destructive disassembly and monitoring techniques are key DfD enablers. The studies have argued the need for comprehensive changes, encompassing regulatory support, industry-wide adoption of DfD principles and advanced connection technologies.

Through the creation of enduring designs that prioritize DfD/A, iIt is possible to actively contribute to the development of structures that not only enhance social well-being but also possess long-term sustainability. Strategies for adaptability encompass potential future expansion, simplified and reversible connections, flexible layouts and standardized components. The proposed systems include reusable timber slab-and-column structures that offer flexibility in design and parallel assembly and disassembly. These approaches aim to extend the service life of timber buildings, reduce waste and enhance resource efficiency, aligning with the transition towards CE in the construction sector.

Consequently, in recent years, there has been a significant surge in research efforts focused on advancing DfD/A principles within construction, especially for timber structures. The most important DfD principles for timber structures have been condensed according to several authors and bibliographic searches, these being: ease of access to components, ease of disassembly, independence, simplicity, standardization, documentation and mechanical joints, among others. Several tools and frameworks have been developed to evaluate and facilitate DfD and circularity in construction projects, representing a powerful instrument in combination with BIM tools. This expanding body of research encompasses a wide array of methodologies and tools developed to enhance sustainability, efficiency and circularity in the construction industry. Recent standards such as the ISO 20887 [77] are an example of this recent increase in popularity.

Prefabrication and modularization have a central role in advancing sustainability, adaptability and circularity in timber construction. Innovations in prefabricated timber technology are enabling houses to adapt to evolving household needs and preferences, fostering a responsive approach to design. Prefabricated assemblies and dismountable mechanical connections are deemed essential in DfD to ensure the preservation of reusable components and aligning with planning phase expectations. Despite the abundant forest cover and a well-developed European prefabricated timber building industry, the potential of multistorey timber construction remains underexplored [105]. The growing trend toward prefabrication and volumetric modules in timber construction is reshaping conventional notions of adaptability. Researchers are exploring innovative structural solutions, showcasing the pivotal role of prefabrication in these developments.

Prefabrication also aligns with CE principles, offering benefits such as material reuse and renewable properties, contributing to sustainable building practices. Various design strategies, including mechanical and reversible connections, load-bearing elements, and prefabricated structures, are being employed to facilitate the disassembly and reuse of timber components [30]. High levels of prefabrication are recognized as a key driver for advancing circularity, streamlining assembly processes and reducing construction waste. The importance of prefabricated components and connectors is underscored across multiple studies, highlighting their role in achieving DfD principles. Emphasizing the regional context, researchers stress the need for adaptable design guidelines considering variations in prefabrication levels and material choices [65]. Prefabrication stands as a pivotal factor in enhancing sustainability, adaptability, and circularity in timber construction, driving innovation and reshaping industry practices.

The analysis of project programs revealed that a significant majority (66 %) of the projects incorporating timber structures and DfD were in the residential sector, particularly, in residential buildings with four floors or fewer. The office program followed at 16 %, while social buildings constituted 13 %. Commercial use and other purposes had a marginal presence at 3 % each. When focusing on the number of stories, 60 % of the buildings had four floors or fewer. Buildings with 5–8 stories made up 29 % of the buildings, with a limited number of buildings exceeding 8 floors (10 %).

Timber buildings designed following DfDR principles can significantly reduce GHG and provide various environmental benefits over demolition and even recycling-focused construction approaches. The circular qualities of MT products can be demonstrated through processes like C2C certification, clarifying both the initial and EoL qualities. Research shows that developing deconstruction options and designs can significantly reduce CO_2 emissions and costs when compared to the initial alternatives, with reuse offering notable environmental and economic benefits. High prefabrication levels are seen as a potential facilitator of circular construction, while methods for assessing the environmental impact of disassembly and selective demolition processes can help minimize waste at the end of a structure's life cycle.

Durability, when considered alongside adaptability and reversibility, plays a vital role in fostering sustainable and circular construction practices. Durability is a prerequisite for successful disassembly and subsequent reuse. It is necessary to integrate durability and maintenance considerations when applying CE assessment indicators, especially in MT buildings [58]. Several strategies, such as the use of high-quality materials, densified nails, solid wood components, and self-drilling screws, contribute to durability and reversibility. Protection from adverse conditions also enhances timber durability. Vandamme and Rinke [36] shed light on the paradox that modern timber structures designed for longevity are often demolished not due to technical issues but vacancy, emphasizing the need for enhanced adaptability. Design for durability and repairability emerges as integral circularity strategies. Dams et al. [32] emphasize the importance of accessible mechanical connections and manufacturing-style approaches using durable, standardized components for circular construction. The importance of satisfying the need to standardize the measurement of the durability of structures designed to be disassembled has been shown, through NDT, in situ and rapid methods and even monitoring during the useful life of the structure, to successfully carry out structures designed to be disassembled.

The main challenges for the development of DfD/A in timber construction are summarized in Table 3. The research highlights the potential for reclaimed timber from dismantled structures, particularly those with large cross sections, to be reused effectively in construction. While reclaimed wood offers considerable promise for sustainability, it also poses challenges due to its higher variability in mechanical properties compared to new timber. Grading and testing standards need to be updated to accommodate reclaimed timber's unique characteristics. The density values of reclaimed wood are similar to those of new timber, and the stress wave velocity remains consistent between the two, making NDT a reliable predictor for both materials. Testing on deconstructed lumber from historic buildings demonstrated the feasibility of reusing these elements. Also, laboratory tests show that properly assessed. Reclaimed timber, even up to 130 years of age, can be integrated into new structures. Standardized cross-sections and advanced grading techniques, including NDT like visual inspection and machine grading, can enhance the market acceptance of salvaged timber. To further promote timber reuse, post-use certification and strength testing play a crucial role [104] and timber components still need to be verified

Table 3
Main challenges and gaps for the development of DfD/A in timber construction.

Challenges and gaps for DfD/A in Timber Construction	Key Points
Labor-intensive disassembly processes	Disassembling timber structures can be labor-intensive, hindering efficient DfD/A implementation.
Regulatory hurdles and industrial adoption	Existing regulations may not fully support or incentivize DfD/A principles, requiring overcoming regulatory challenges and industrial adoption.
Standardization and documentation	Achieving standardized practices and comprehensive material documentation is crucial.
Lack of demand for salvaged materials	Despite potential material reuse, there's a lack of market demand for salvaged timber, impacting economic viability.
Grading, standardization and certification of salvaged timber	Grading reclaimed timber, updating testing standards, and addressing variability suppose obstacles to effective reuse.
Shift towards non-destructive disassembly	Adopting standardizations and regulations of non-destructive disassembly methods and continuous structure monitoring is essential.
Durability	While recognized as pivotal, requires more comprehensive integration with CE assessment indicators.
Innovative connection systems	Implementation of innovative connection systems for efficient disassembly and minimal damage needs further development.
Application since initial project phases	Effective implementation of adaptability and disassembly strategies, such as reversible connections and flexible layouts since the start of the project.
Prefabrication challenges	Underexplored potential of multistorey timber construction and reshaping adaptability notions through prefabrication.
Application beyond residential and office use	Untapped potential for the implementation of DfD/A timber structures in commercial and other multi-purpose projects
Adaptation to regional variations	Aligning prefabrication with CE principles requires addressing regional variations and diverse prefabrication levels.

before they can be reused. Overall, the research has demonstrated that reclaimed timber, if carefully evaluated and processed, allows DfD to be carried out.

5. Conclusions

This study presents a literature review on the progress of DfD/A timber structures. A total of 129 studies published between 2000 and 2023 including nine different research fields were analyzed. This extensive body of research shows that:

- Embracing circular construction principles in today's construction industry, particularly those centered on DfD/A, is crucial to reduce waste production and carbon emissions. Timber construction emerges as a promising avenue for achieving circularity in building design, given its natural modularity and renewability, aligning with DfD/A principles. By prioritizing adaptability in design, architects and engineers can contribute to the creation of structures that enhance social well-being for the occupants and promote long-term sustainability.
- There has been a growing emphasis on DfD/A principles, particularly in timber construction, accompanied by the development of tools, methodologies and checklists to support these concepts. Prefabrication and detachable connections play a central role in promoting sustainability, adaptability and circularity in timber construction, leading to a transformation of the traditional construction practices. The analysis further highlights that most of the timber structures designed according to DfD/A principles consist of low-rise residential buildings, particularly those with four floors or fewer.
- Durability plays a pivotal role in the circularity of timber construction, facilitating successful disassembly and reuse. High-quality materials, standardized components and protection from adverse conditions contribute to durability. The research shows the potential of reclaimed timber from dismantled structures, provided it undergoes careful evaluation and processing, while innovative connection systems and standardization play a key role in enabling DfD/A in timber construction.
- In recent years, innovative approaches have been developed, encompassing reusable timber systems and advanced connection methods. The research has explored structural performance and energy efficiency in different geographical contexts as well as the potential of timber construction in specific projects. The reusability and performance of timber structural elements have been evaluated, including post-tensioned timber frames, bending-active timber structures with interlocking connections and recovered wood structures, aiming to extend their service life and design possibilities.
- However, there are still notable gaps and challenges that require attention. It is necessary to effectively implement adaptability and disassembly strategies from the start of a project. The labor-intensive nature of disassembly processes, regulatory obstacles and the limited demand for salvaged materials remain significant hurdles. Standardization, documentation and non-destructive mechanical tests need further refinement to streamline the adoption of DfD/A principles. The marginal presence of commercial and other-purpose projects incorporating DfD/A timber structures indicates potential untapped areas for implementing circular construction. Additionally, the need for adaptable design guidelines, especially in regions with varying prefabrication levels, highlights the importance of context-specific approaches. While recognized as pivotal, durability requires a more comprehensive integration with CE assessment indicators. Grading and testing standards need to be updated to ensure the effective reuse of reclaimed timber. Addressing these gaps will be crucial for advancing the circular economy and sustainable timber construction in the future.

CRediT authorship contribution statement

Mañes-Navarrete David: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Redón-Santafé Miguel:** Writing – review & editing, Validation, Supervision, Conceptualization. **Paya-Zaforteza Ignacio:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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