Disassembly and Reuse in Tall Timber Buildings: Advancing Circular Construction Practices

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Abstract. The construction industry is a major contributor to global CO_2 emissions, necessitating innovative solutions to reduce its environmental footprint. Tall Timber Buildings (TTBs) represent a sustainable alternative to traditional construction methods by leveraging engineered wood products like Cross-Laminated Timber (CLT) and Glued-Laminated Timber (GLT). However, conventional linear design processes limit the sustainability potential of TTBs. This paper explores the role of Design for Disassembly (DfD) in enhancing the reuse and recycling of timber components, aligning with circular economy principles. Key strategies such as modular design, reversible connections, and the adoption of digital tools like Building Information Modeling (BIM) are discussed. Challenges, including regulatory barriers and material degradation, are addressed alongside case studies highlighting successful TTB projects. By embracing DfD principles, the industry can extend material lifecycles, reduce waste, and transition toward a regenerative built environment. This work underscores the importance of collaboration across disciplines to achieve sustainable construction goals.

Keywords: Tall Timber Buildings · Design for Disassembly · Reversible Connections · dismantle · Demountability

1 Introduction

1.1 Relevance of Taller Timber Buildings

The construction industry is increasingly focused on decarbonization, since it is responsible for 40% of global CO_2 emissions [1], with cement production contributing a significant share. This, combined with urban densification trends that demand sustainable housing and infrastructure solutions, has driven the development of Taller Timber Buildings

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(TTB). TTBs leverage the sustainability advantages of timber and the performance of Engineered Wood Products such as Cross-Laminated Timber (CLT), Glued-Laminated Timber (GLT), and Laminated Veneer Lumber (LVL) to meet current engineering and construction requirements.

However, a "linear" design, construction, demolition, and disposal process for TTBs is not sufficient to mitigate the current environmental impacts of the built environment. Instead, adopting approaches based on circular economy concepts offers an opportunity to reduce the demand for raw materials and further decarbonize the built environment by extending the lifespan of material resources through reuse and recycling [2]. By embracing these principles, timber buildings can shift from the traditional "take-make-dispose" model to a "reuse-recycle-retain value" framework (Fig. 1).

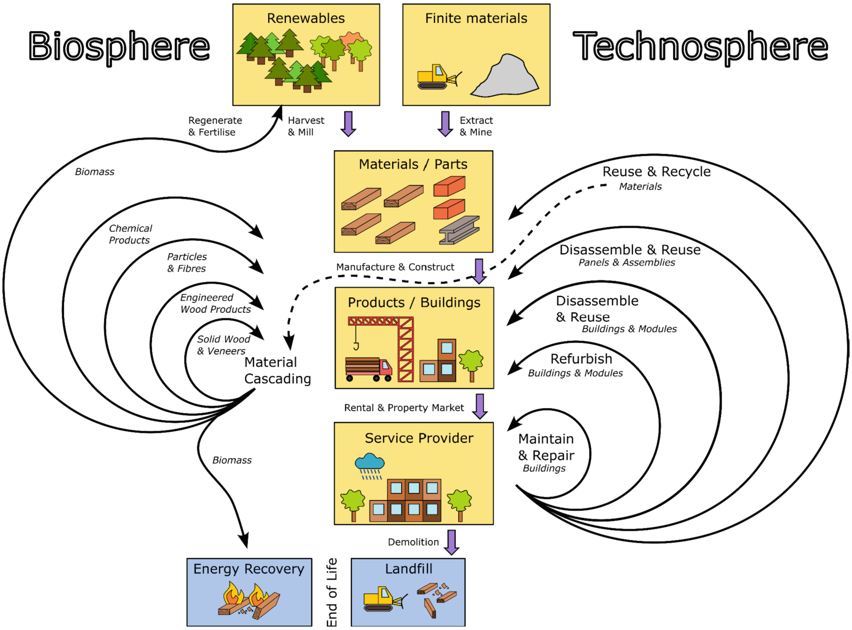

Fig. 1. Product and material streams of circular timber buildings [3].

1.2 Design for Disassembly in Taller Timber Buildings

In developing circular concepts and designs for TTBs, Design for Disassembly (DfD) is essential not only to maximize the reuse potential of construction components but also to enhance the adaptability and repairability of buildings, thereby extending their service life [4, 5]. DfD involves designing buildings, or parts of buildings, to be easily replaced or dismantled and reassembled, aiming at components being reclaimed with minimal processing.

Key principles guiding DfD include: i) Modularity – the building is designed so that certain parts or components can be replaced without compromising the integrity of the whole structure (this requires a clear separation between the primary load-carrying structure and other components); ii) Demountability of connections – using standardized parts and reducing complexity to allow easy separation without damaging components, thus enabling reuse.

It is important to acknowledge Brand's concept of a building as "shearing layers of change" [6], which recognizes that building components have different lifespans. Thus, modification and adaptation of the different building parts to new functions and requirements must be simplified. Moreover, DfD aligns with the concept of "buildings as material banks," where materials are viewed as valuable resources rather than waste [5].

1.3 Tools and Technologies Enabling DfD

The adoption of digital tools such as Building Information Modeling (BIM) enhances DfD by providing accurate documentation of components, connections, and their assembly sequence. Material passports and digital twins further facilitate the tracking of components, ensuring their reuse potential is preserved [7]. Prefabrication plays a pivotal role in DfD by allowing components to be manufactured offsite in optimal conditions and with minimal waste and then assembled onsite. If done correctly, this may later allow for a clean removal of those components. However, the prefabricated components themselves might not be optimized for disassembly, like a prefabricated shear wall or floor segments with nailed or stapled wood-based sheathing.

2 Rationale for DfD in Tall Timber Buildings

2.1 Advantages of DfD

Buchanan [8] identified the major challenges in TTBs as fire, wind, earthquakes and moisture; challenges which also exist for low- and mid-rise mass-timber buildings that become 'more severe as the buildings get taller' [8]. Successful 'holistic' design for all requirements (serviceability and load-carrying capacity, durability, acoustics, etc.) requires significant collaboration across teams and disciplines [9]. As timber buildings get taller, the consequence of failure increases and retrofit and repair become more costly. Provision of insurance depends on the risk profile of buildings to estimate the potential for loss and on the ease and cost of repairs [10]. Tall timber structures, such as multi-story timber temples and pagodas, have a long history in Asian vernacular architecture [11]. Their existence through time is in part owed to regular maintenance and repair, including 'repair by disassembly' (解体修理 *kaitai shūri* in Japanese), with evidence that some temples were (partially) disassembled and repaired as early as 1596 [12]. It thus seems obvious to design modern timber structures such that they can be regularly inspected, maintained and repaired by selectively replacing components. In addition to longevity, DfD provides several more advantages at the end of the life of a timber building:

In terms of environmental benefits, DfD enables the reuse and recycling of materials, which minimizes waste generation and conserves natural resources [13]. In the timber industry, where reliance on forests is significant, DfD ensures harvested wood is utilized efficiently across multiple lifecycles [14].

DfD also offers economic advantages by fostering a secondary market for reclaimed timber components, creating opportunities for material resale. Additionally, integrating DfD principles enhances the financial viability of timber buildings by reducing long-term lifecycle costs, such as through design for structural adaptation [15].

2.2 Challenges of DfD

Several challenges must be addressed for the effective implementation of DfD in TTBs. Structurally, TTBs must meet load-carrying, serviceability, fire safety, durability, and other standard requirements while also accommodating the additional demands of demountability and, if applicable, reusability. Achieving disassemblable connections that remain functional over multiple cycles requires initial overdesign, and components must retain their dimensional stability and structural integrity for reuse [4, 16, 17]. Consumer perception of reclaimed timber can affect its uptake, while on the policy front, DfD faces barriers due to the lack of regulatory frameworks that promote circular construction [18]. Policies that incentivize sustainable design and material reuse are essential, as highlighted by the inclusion of reuse maximization in the new EU Construction Products Regulation [19]. Addressing these technological, social, and regulatory challenges is critical for advancing DfD in the timber industry.

3 Types of Connections

From a design perspective, reversible connections are a key component in developing a successful strategy for DfD. Reversible connections, defined as those that combine ease of disassembly with the reuse potential of both the connection and the joined members, are relevant in this context. Ottenhaus et al. [4] provide a detailed description of the several existing types of structural timber connections (i.e., carpentry, with mechanical fastener brackets, proprietary systems, glued, etc.) and their potential for DfD.

Historic examples show the potential of carpentry connections [13]. However, shrinkage, swelling and visco-elastic deformation in timber can pose challenges for disassembly, particularly in parts produced using CNC machinery and very low tolerances. Connections with common dowel-type fasteners like nails and screws exhibit limited potential for reuse. Nails are difficult and labor-intensive to remove, while screws are sometimes impossible to remove, either because of rupture or because their head breaks when attempting to remove them [20]. Yet, experiments have shown that new screws inserted in holes from previous screws loaded in shear in the elastic range exhibited the same stiffness and load-carrying capacity [21]. Connections with dowels and slotted-in steel plates have been used in reusable sports buildings in Switzerland due to the ease of assembly and disassembly of such connections [22], however moisture fluctuations and shrinkage, as well as overloading, can affect their reversibility [17]. Proprietary brackets have been developed as “plug-and-play” assemblies and may offer reversibility in the elastic range. However, it must be considered how moisture variations, creep, and friction may affect or even hinder disassembly [16].

4 Tall Timber Building Case Studies

The global adoption of TTB underscores the potential of wood products as potentially more sustainable alternatives to traditional construction materials, particularly concrete. Recent projects, such as HAUT in Amsterdam and Mjøstårnet in Norway (Table 1), exemplify the viability of TTBs by demonstrating their ability to compete with steel and concrete in terms of performance and architectural design.

Table 1. Tall timber buildings inventory based on their year of completion.

Building name	Location	Height, Stories	Key features	Disassembly potential
Treet	Bergen, Norway	49 m, 14, 2015	Prefabricated modules, entirely timber structure	High - Prefabricated modules allowing full disassembly
Brock Commons Tallwood	Vancouver, Canada	53 m, 18, 2017	Hybrid structure with CLT panels & concrete cores	Low - Hybrid structure with concrete cores
25 King	Brisbane, Australia	45 m, 10, 2018	Australia's tallest timber building, featuring CLT and glulam	High - Modular prefab. Construction CLT & glulam
Mjøstårnet	Brumunddal, Norway	85 m, 18, 2019	Tallest timber building at completion, glulam and CLT construction	Medium – Prefab. components w. limited modularity
HoHo Wien	Vienna, Austria	84 m, 24, 2019	Mixed-use, hybrid timber-concrete design	Medium - Hybrid design with some prefab. Components
Sara Kulturhus	Skellefteå, Sweden	75 m, 20, 2021	Multi-functional building, CLT structure	High - Modular CLT components designed for sustainability
HAUT	Amsterdam, NL	73 m, 21, 2022	Hybrid construction with timber and concrete, focus on sustainability	High - Modular components with a hybrid design
25 King	Brisbane, Australia	45 m, 10, 2018	Australia's tallest timber building, featuring CLT and glulam	High - Modular prefab. Construction with CLT and glulam

5 Learnt Lessons and Challenges in Disassembly

As building heights exceed 30 m (approximately 8–10 stories), significant structural challenges arise [23]. At this scale, timber-only construction often becomes impractical, necessitating hybrid systems with steel or concrete to ensure structural stability [5]. These materials are typically used in critical components like reinforced cores and connections to enhance resistance to wind, seismic forces, and vertical loads [24]. However, the trade-off between connection efficiency and demountability complicates disassembly.

As timber buildings grow taller, integrating DfD principles becomes more complex. DfD emphasizes adaptability, modularity, and material reuse, aligning with circular construction principles. Yet, hybridization, e.g. with concrete casted on site, may reduce disassembly potential and limit circularity. Addressing these trade-offs requires innovative approaches to balance structural demands and sustainability, ensuring timber remains a viable low-carbon alternative in high-rise construction.

6 Learnt Lessons and Challenges in Reuse

A key challenge limiting the structural reuse of timber members has been the absence of grading standards for the recertification of salvaged timber [25]. The recent introduction of FWPA Standard G01 [26] and prNS 3691 [27] represents a significant step toward enabling the reuse of recycled timber. However, these standards do not address the (re)certification of engineered wood products, which constitute the majority of structural timber in TTBs. Additionally, grading salvaged timber often results in significant downgrading due to unknown load histories, undermining the financial viability of reuse [18]. Demolition remains more economically attractive than deconstruction due to high labour costs and limited residual timber value. Recent research into reversible timber connections shows promise for facilitating disassembly and reuse [4], but challenges persist with both proprietary and bespoke systems, particularly regarding ease of disassembly [16, 17]:

- Non-Reversible Deformations: Wood fibres may swell, shrink or deform during the service life of the building, making it difficult to demount connections [16]. Even when connections are demountable, residual deformations may reduce the fit and performance of reused connections. Controlled pre-compression during initial assembly, as well as innovative designs that provide sufficient tolerances, can help mitigate these effects.
- Corrosion of Metal Components: Metal fasteners may degrade over time, complicating disassembly and reuse. Advances in corrosion-resistant alloys and surface treatments are helping address this challenge.
- Assessment of Structural Integrity: Components must be inspected and regraded to ensure their suitability for reuse, particularly in load-bearing applications. Non-destructive testing methods, such as ultrasound and X-ray imaging, are increasingly used to assess the condition of timber components and timber joints.
- Wear and Fatigue: Repeated cycles of assembly and disassembly can lead to fatigue in connectors and increased tolerances, particularly in high-stress applications. Solutions like sacrificial layers or replaceable connector components are emerging to address these issues.

7 Conclusion

The disassembly and reuse of timber connections are central to achieving sustainable construction practices, particularly in Tall Timber Buildings (TTBs). By integrating Design for Disassembly (DfD) principles, the industry can extend the lifecycle of timber components, reduce waste, and enhance resource efficiency.

While technological advancements have improved the feasibility of DfD, challenges remain in addressing material degradation, connection durability, and regulatory barriers. Collaborative efforts between designers, engineers, policymakers, and manufacturers are essential to overcoming these obstacles and promoting circular construction practices.

Timber buildings present unique challenges in regard to disassembly, in comparison to other structural materials (i.e. steel). Furthermore, hybrid structures can complicate disassembly workflows and should be carefully addressed in the design process; conversely, the use of precast concrete panels and beams may offer advantages by facilitating DfD.

The future of TTBs lies in balancing performance, sustainability, and adaptability. By prioritizing disassembly and reuse, the timber industry can lead the transition toward a more resilient and regenerative built environment.

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