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Reusable timber modular buildings, material circularity and automation: The role of inter-locking connections

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ABSTRACT

As sustainability becomes a central concern in construction, the industry witnesses a significant surge in the adoption of material circularity principles, reflecting a new approach to resource management. Although mass timber construction holds significant potential for end-of-life (EoL) material circularity due to its natural materials and prefabrication, conventional connection systems hinder material reuse. Integrating interlocking techniques into modular construction could enhance circularity and enable future autonomous construction. This paper summarises design-for-reuse (DfR) strategies focusing on connection design for rapid assembly and disassembly of Cross-Laminated Timber (CLT) modules. These strategies can promote innovative connections with enhanced material circularity, which were illustrated through a recently proposed conceptual interlocking connections (MOD-IT). Additionally, a comparative cradle-to-cradle Life Cycle Assessment (LCA) evaluates the environmental impact and circularity potential of timber modular buildings using this connection system. The study underscores the pivotal role of strategic connection design in achieving a closed-loop system in timber construction. This advancement fosters sustainability by improving efficiency, adaptability, reusability, and autonomy in the construction process.

1. Introduction

Timber modular construction (TMC), a modern method of construction (MMC), offers remarkable gains in efficient building practices (e.g., reduced construction time and impact, labour costs, higher quality of onsite operation) by employing off-site fabrication of standardised modules. By embracing renewable timber materials that exhibit lower embodied energy, TMC emerges as a promising solution for mitigating the substantial environmental footprint associated with the construction industry. The continuous evolution of TMC, coupled with the growing global interest in timber-based construction, has led to the World Bank's forecast of a fourfold increase in timber demand by 2050 [1]. This growth, however, raises concerns about the sustainable sourcing (supply) of engineered timber, given the anticipated increase in timber-constructed buildings [2], making material circularity an important topic within the context of timber construction.

Mechanical connections are the crucial parts in promoting systematic circularity, while the development of which is still in early stages due to TMC's recent emergence as a construction technology. Current connection options, such as angle brackets and hold-downs, often fall short due to labour-intensive installation, limited capacities, unpredictable behaviours, and risks of brittle failure

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[3], which hinder the reusability of timber. With increasing concerns over material shortages and the need for material circularity, the industry is shifting towards connection solutions that enhance efficiency, adaptability, and reusability. Consequently, new timber connectors have been developed to support adaptable large timber structures, as detailed in previous studies [3–5]. Among these, interlocking techniques—rooted in ancient Asian architecture (Fig. 1) and known for minimal operational requirements and instant activation [6–8] —are being adapted for modern construction with improved accuracy, efficiency, and mechanical performance, utilising a broader range of materials like steel and advanced polymers. Likewise, employing interlocking connections in TMC could ease the disassembly and reassembly of modules, facilitating easy retrofitting, relocation, or repurposing of structures, thereby supporting circular economy principles by extending material lifespans, reducing waste, and minimizing raw material extraction. Despite its advantages, the interlocking technique is still relatively new to modern construction and not widely understood, highlighting the need for further research to encourage broader implementation.

This paper begins by exploring strategies for connection-related circularity design in buildings through reviewing existing research in this area. A recently proposed interlocking system uniquely crafted for CLT panelised and volumetric structures is discussed thereafter. This system offers important insights into how interlocking connection techniques can improve assembly efficiency and material reuse in timber modular construction, while also supporting autonomous building processes. Additionally, the potential of this joining technology to enhance dismantlability and material circularity is assessed through a preliminary LCA study on timber buildings reinforced by traditional and interlocking connections.

2. Design for circularity in buildings

2.1. Building circularity overview

Despite the UK generating over 60 million tonnes of construction and demolition waste annually, there remains a notable lack of focus on the EoL of building materials and their potential for reuse [6]. The Green Alliance has estimated that increasing the reuse of construction products could save 22.3 MtCO2e of greenhouse gas emissions over 9 years [7]. Therefore, driven by the increasing emphasis on material circularity, the reuse and recycling of building materials have become pivotal areas of research. Being a biodegradable and easily modifiable material, timber has greater potential for reuse over other mainstream construction materials. However, a significant portion of wood sourced from the construction and demolition (C&D) sector can now only be subject to disposal methods such as incineration for energy retrieval or placement in landfills, contingent upon the specific legal, regional, and technological contexts in each country [10]. This approach aligns with the least favoured option in the waste hierarchy (Fig. 2). Currently, Europe recycles only about one-third of its wood waste into materials suitable for board product manufacturing [11], indicating the urgent need to improve systematic circularity in construction.

To ensure optimal systematic circularity across the entire building system, holistic considerations—including manufacturing, business models, disassembly plans, and reverse cycles—should be implemented from the outset of a product's design [12]. Various design guidelines have been proposed to improve the potential of systematic circularity in different stages of construction, such as design for manufacturing and assembly (DfMA), for flexibility (DfF), for adaptability (DfA), for disassembly (DfD), and for Reuse/Recycling (DfR) [13,14]. These are also the fundamental principles included in the Circular Economy Statements [15]. Yet, there is not a globally recognised standard for such practices, and researchers tend to propose unique guidelines, methodologies and criteria that are tailored to specific projects, products, and design requirements [13,16].

2.2. Design connection for reuse

Reusing materials is one of the most sustainable EoL approaches as demonstrated in Fig. 2, as it facilitates closed-loop material circularity in the supply chain instead of the conventional linear way, consequently minimizing the need for virgin materials in manufacturing. Recognising this sustainable potential and its critical role in the construction ecosystem, the focus has shifted towards

(a) (b)

Fig. 1. The tallest and oldest existing timber tower in China (a) Yingxian wooden pagoda, first built in 1056AD, and (b) its interlocking connection details [9].

Fig. 2. Waste hierarchy.

developing effective strategies to optimise this process. Therefore, a growing body of research has focused on formulating general principles to guide DfD, aligning with the growing interest in structural deconstruction. As summarised by Akinade et al. [17], Kanters [18], Tzourmakliotou [19], and Kim [20], most of the proposed DfD principles can be classified as *Building Materials* related (e.g., avoid toxic and composite material, simplify building components and adopt lightweight, durable and separable material and joint), *System Design* related (e.g., employ modular, offsite and standardised construction, and accessible joint, building components, and service), *Human* related (e.g., provide adequate tools, training and communication, document material to ensure traceability and identifiability, and quantified information of cost and environmental impact) and *Policy* related factors (e.g., incorporate in building codes, set compulsory targets for deconstruction and material recycle and reuse). In addition to the general DfD principles, there are hundreds of indicators/criteria proposed for measuring the DfD performance of products and structures.

However, it should be noted that the incorporation of DfD principles in building design does not inherently guarantee the reusability of the components. While these principles facilitate deconstruction, it is equally important that the detached components sustain minimal damage and retain sufficient capacity for subsequent reuse [5,15,17]. This consideration leads to the identification of two primary objectives in design for reuse (DfR); one is the ease of separation of structural components, and the recovery process of structural members. Given that deconstruction involves breaking connections between components, connection-related factors rank among the most crucial in DfD and DfR indicators, underscoring their importance in the effective implementation of circularity principles in construction.

Table 1 presents an overview of the published DfR criteria related to connection design, complete with a weighted scoring system derived from a Likert scale. Each criterion under a KPI is assigned a score between 0 and 1, with the overall weighting score contingent upon the number of available criteria per KPI. Criteria crucial to achieving systemic circularity receive higher weightings. As summarised in Table 1, the connection design can impact the circularity of buildings from different aspects. Some features of connection, including types, uniformity, accessibility and level of prefabrication decide not only the possibility, but also the ease of deconstruction (time, cost, and labour requirements of deconstruction). The remaining factors (deformation, complexity, standardisation) primarily concern the reusability of building components. Connection designs that eliminate the need for cutting and prevent structural damage preserve the integrity of materials and ensure their second life cycle. However, components that are dismantled integrally means that they will require heaving machine to lift and transport, thereby potentially escalating the costs associated with their reuse.

According to Table 1, standard timber connections such as angle brackets and hold-downs demonstrate suboptimal performance regarding DfR. While disassembly is possible, it requires a laborious de-nailing/unscrewing process or cutting the screwed timber sections, leading to increased cost and waste, as well as unstandardised timber dimensions that are only suitable for energy recovery (incineration) or making by-products (Fig. 8). The disassembly efficacy of other existing timber connection solutions has been extensively evaluated in prior studies [5,22,23]. It is worth noting that CLT panels are not good candidates for recycling due to the resin used between the laminated timber, however, CLT can be refurbished and reused.

3. Interlocking connections

3.1. *Demountable interlocking connection systems overview*

Enabling material circularity in the construction industry necessitates the development of 'plug-and-play' systems featuring demountable connections. Therefore, modern adaptations of ancient interlocking techniques have been examined to enable smooth assembly and disassembly, thereby advancing the principles of the Circular Economy (CE). The fundamental concept of using the interlocking connection is to replace existing onsite connections with those that can lock the structural elements by the interaction between components. These practical systems provide adaptability and suitable mechanical properties for various kinds construction. Research indicates that their resulting shorter labor and installation times can enhance the financial and environmental performance of projects [2,25,].

The utilisation of interlocking (including self-locking) techniques in connection design is recently gaining increasing interest in the modular construction of both concrete [26,27] and steel [7,8,28–33]. Within modern timber construction, the interlocking method is more widely seen in timber framed structures. Unlike traditional interlocking connections directly applied to the ends of timber components, current products for timber-framed buildings, such as the RICON® connector from KNAPP and HVP connectors from

Table 1
DfR connection design criteria and weightings.

Connection DfR Principles	Key Performance Indicators (KPIs)	Criteria	Weightings
Implementing reversible connections that allow for ease of deconstruction [8,13,16,17,21–23]	Connnection Type	Dry connections (e.g., click, self-locking connections), which can be directly dismantled without damage	1.00
		Connections incorporating supplementary items like screws, bolts, and nuts that can be detached using manual tools	0.75
		Direct integrated connection (e.g., pin, nail), which can be dismantled by minor modifications with power tools	0.50
		Soft chemical connection that can be dismantled with moderate damage using power or gas tools	0.25
		Hard chemical connections (e.g., glue, weld, cement bond) can be dismantled with hydraulic tools that cause significant damage	0.10
Minimisation of structural connection types [23]	Connection Uniformity	A single connection type is consistently used throughout the structure	1.00
		Different connection types are adopted for shear and tensile connections separately	0.50
		Multiple connection types are used due to complex structural design requirements	0.10
Reduced cutting/modification on structural material for connection fitting to avoid additional workload and waste generation [22]	Connection Complexity	No modifications are needed	1.00
		Simple cutting on material is required	0.50
		Complex modifications are necessary (e.g., longitudinal drilling, multiple cuts for complex geometry)	0.10
Standardisation and market availability of connections [24]	Connection Standardisation	Connections are well standardised and widely adopted	1.00
		Connections are standardised and commercially available	0.50
		Bespoke connection to the project	0.10
The level of off-site integration of connection with buildings system [22]	Connection Prefabrication	Connections are precisely pre-attached to structural elements off-site, arriving on-site ready for assembly	1.00
		Connections require on-site installation	0.10
Mitigation of connection-induced damage to structural elements [5,17,24]	Connection Deformation	Deformation during the structure's service life does not damage the structural elements, allowing for complete reuse of material	1.00
		Structural elements and connections accommodate deformation together, allowing for partial reuse of material	0.50
		Structural elements are the main source of ductility and may undergo significant deformation that limit reusability	0.10
Accessibility of connections for maintenance and longevity [13,16,17,24]	Connection Accessibility	Connections are fully accessible from all sides without damaging finishing layers	1.00
		Connections are accessible with additional non-damaging actions (e.g. removing wall finish)	0.67
		Connections are accessible with actions causing reparable damage (e.g., partial demolition of finishes)	0.33
		Connections are not accessible without causing irreparable damage	0.10
Labour and tool efficiency for component transport post-deconstruction [20–22]	Ease of Transportation	Single-person lift: $<$20 kg	1
		Two-person lift:$<$42 kg	0.75
		Hand trolley transport: $<$50 kg	0.5
		Forklift transport: $<$2,000 kg	0.25
		Crane required: $>$2,000 kg	0.1

Pitzl® and APTUS®, often utilise interlocking techniques with metal components. Recent innovations in the connections of timber panelised and volumetric structures have also adopted interlocking methods. These advanced connection systems, shown in Fig. 3, include additional metal connectors that enhance stability and strength. They are particularly beneficial for volumetric structures with extensive timber panels, which face onsite installation challenges due to limited space between components (Fig. 3a and b). Additionally, modern mass timber constructions using engineered elements like Glulam and CLT are easier to disassemble and have fewer structural components. Therefore, using interlocking connections in mass timber constructions can significantly increasing their potential for reuse [34,35].

3.2. Novel interlocking connection and assembly technique

Li and Tsavdaridis [40] recently proposed and tested a new modular interlocking timber (MOD-IT) connection with a controlled deconstruction method. This system is a standardised solution that can be applied to the surface of CLT structural elements without modifications, requiring only adjustments in connector length. In addition to revolutionising on-site construction practices, this connection employs the "Strong Panel-Weak Connection (SP-WC)" design philosophy, which localises damage to specific parts of the connection (fuses), enhances resistance to brittle failure and preserves the integrity of structural elements, enhancing reuse potential.

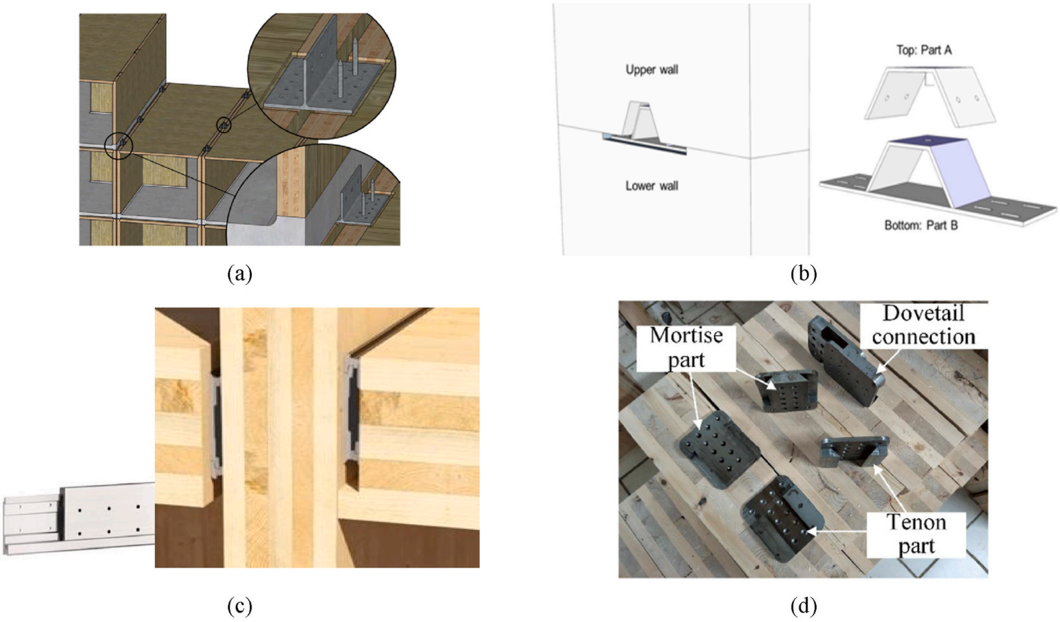


Fig. 3. Novel interlocking metal connections for modular CLT structures: (a) Connection for Jakarta Hotel project [36] (b) An inter-module horizontal connection proposed by the University of British Columbia [37] (c) LOCK Connector from Rothoblaas Ltd [38]. (d) Prefabricated metal dovetail connector [39].

In CLT volumetric construction with MOD-IT connection, as depicted in Fig. 4a, the construction process begins by constructing the core structure, which serves as a lift shaft or staircase, incorporating pre-installed MOD-IT connections. Subsequently, the construction process involves the horizontal sliding of edge flat modules on both sides with tensile connections, and then vertically fitting middle modules with shear connections.

For CLT panelised construction, MOD-IT connections are applicable in both platform-type and balloon-type construction methods. In platform-type CLT structures (Fig. 4b), assembly progresses layer by layer. Wall panels are first slid or stacked atop the base floor panels, with the wall installation sequence strategically determined by structural needs at various building locations. Once walls are in place, the next level's floor panels are affixed atop these walls, culminating in the completion of that floor. In balloon-type CLT structures (Fig. 4c), the construction process begins with the erection of the flooring system with supporting columns. Subsequently, the continuous vertical shear walls are slid along the edges of the floor panels utilising the sliding connections forming the primary lateral load-resisting framework. During the entire insulation process, the connection can be immediately activated after assembly without the need for additional toolings.

This assembly strategy with MOD-IT tensile and shear connections, as illustrated in Fig. 4, effectively creates a network of continuous vertical and horizontal reinforcements within CLT modular systems. Fig. 5 provides clear demonstration of the reinforcing mechanism of this connection across various systems. In CLT volumetric structures (Fig. 5a), the edge modules on both sides are fitted with tensile connections to resist the uplifting, which is normally more significant at the edges, while central modules employ shear connections to resist horizontal movement. This arrangement allows for symmetrical shear and tensile reinforcement at each storey, as shown in Fig. 5a.

A similar reinforcing method can be observed in CLT platform structures (Fig. 5b), in which the panels at the edges are vertically restricted by the sliding tensile connections, and the middle panels are laterally restrained by stacking shear connections. The sliding connections between wall panels can not only ease assembly process, but also ensure lateral integrity while allowing for a certain degree of relative movement. In balloon-type CLT panelised structures (Fig. 5c), sliding connectors serve a dual purpose of connecting the flooring system to the shear walls and ensuring the integrity of shear walls by providing continuous vertical connections between panels.

Previous experimental and numerical investigations on MOD-IT connection system demonstrated its adequate self-locking effect with proper mechanical properties, as well as the damage localisation behaviours [40]. Building on previous research, this innovative interlocking connections and assembly methodology were further illustrated using a scaled-down model (Fig. 6). In this model, 3D-printed unit connectors were attached to the edges of rectangular timber modules. To provide a clear presentation of the connection system and account for the precision limits of 3D printing, the scale used for the connections and modules was not directly proportional. The assembly involved aligning the edge modules precisely, then placing the central module on top, engaging with the sliding connections on both sides. Upon assembly, the structure exhibited certain capabilities of supporting certain vertical and lateral loads as a unified entity (Fig. 7), with minimal movement between the connections, thus demonstrating the potential effectiveness of the interlocking system in structural applications. Compared to other existing interlocking connections shown in Fig. 3, this interlocking connection could offer broader applicability across various structural dimensions, due to the direct attachment on the timber surface. However, the actual mechanical properties and effectiveness in mitigating in-service damage of this connection system in

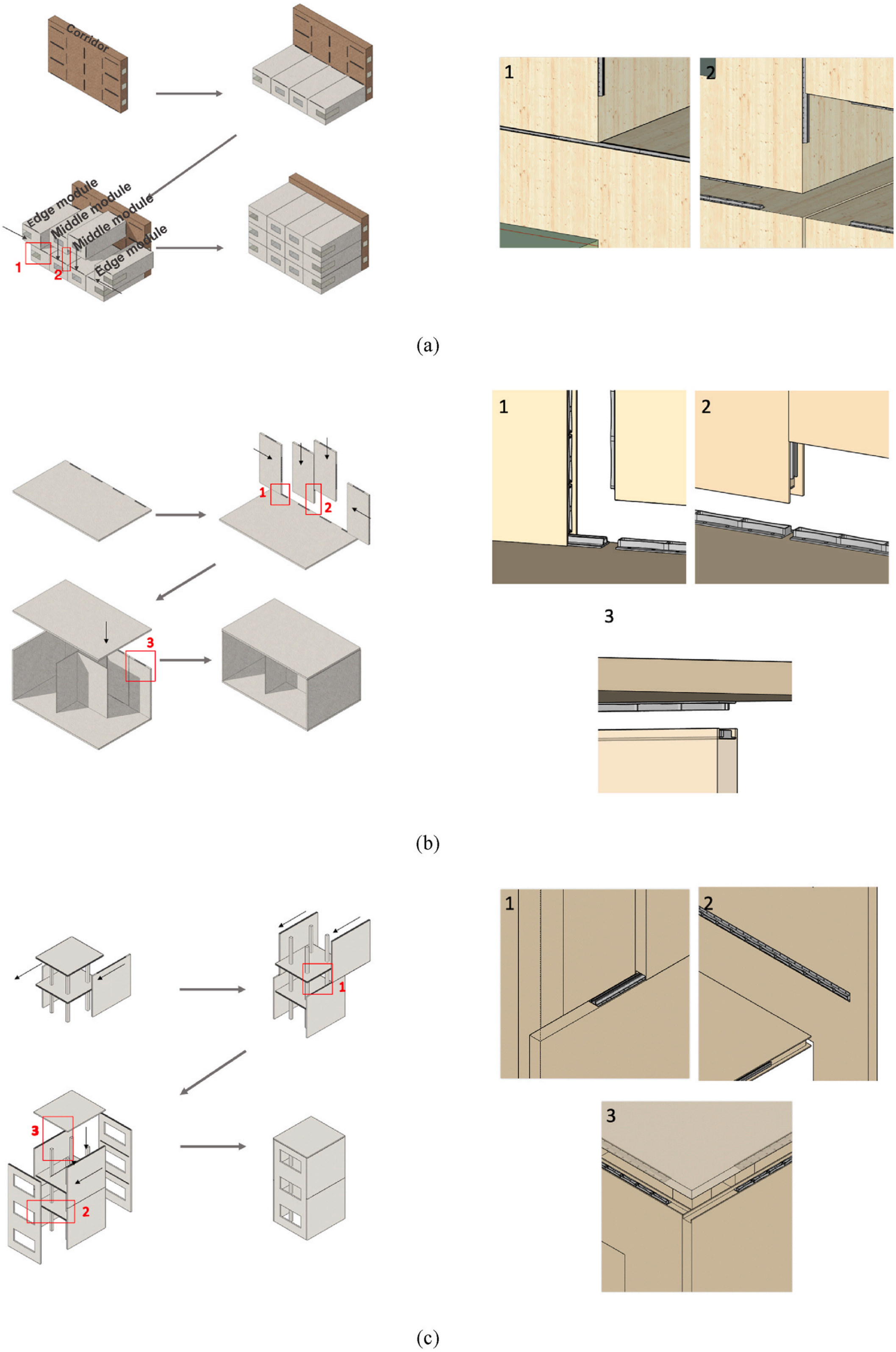


Fig. 4. Application overview of the novel interlocking connection system for different CLT modular structures and the close-up of construction details: (a) CLT volumetric structures (b) CLT panelised platform-type structures (c) CLT panelised balloon-type structures.

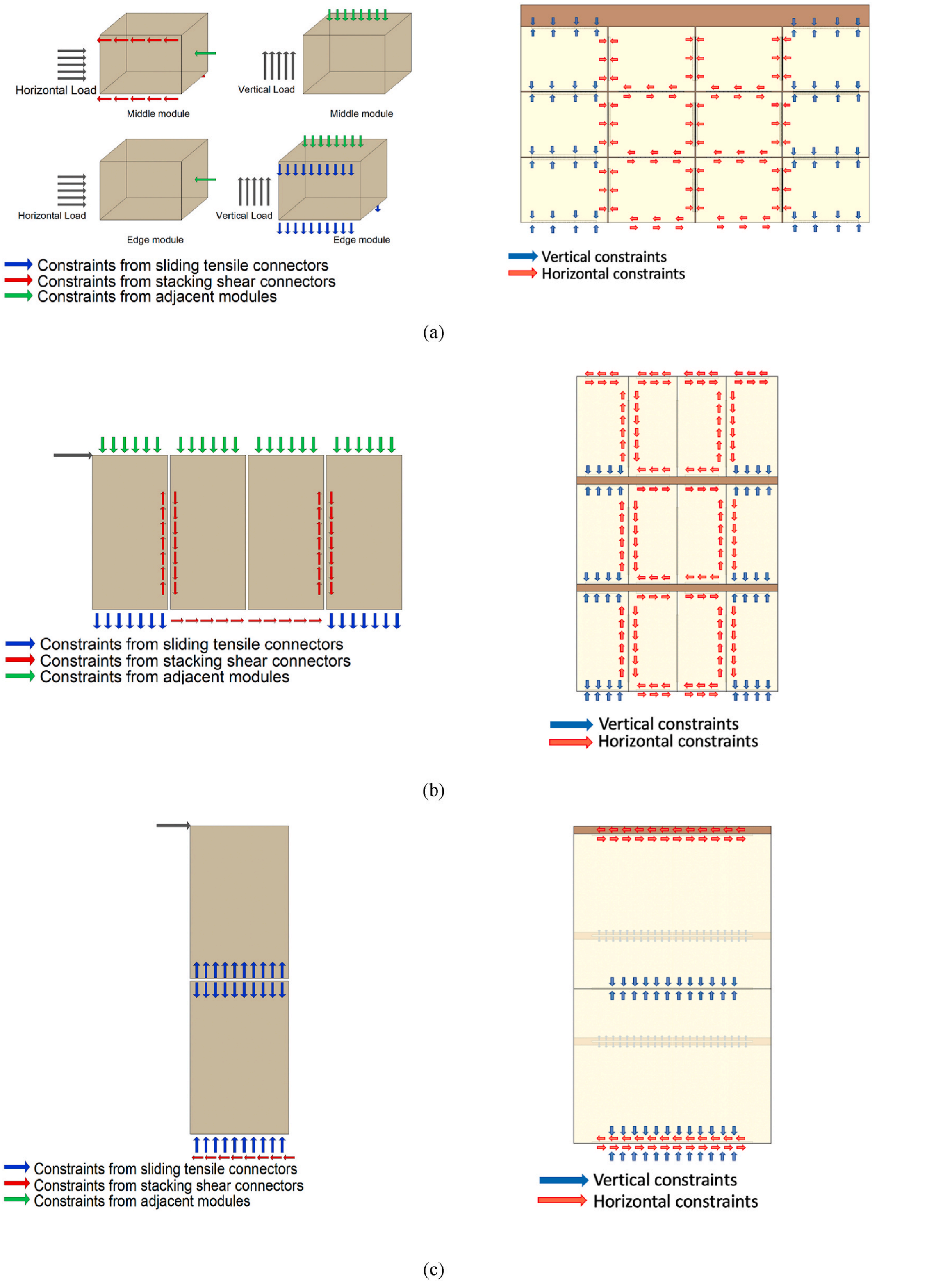
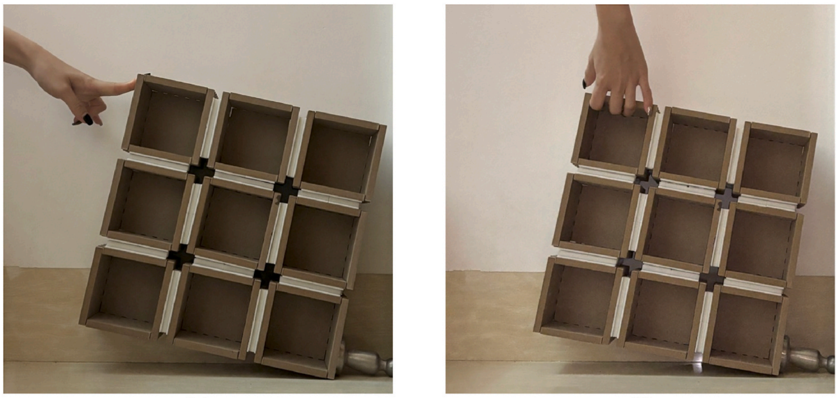


Fig. 5. The illustrations of the interlocking connection working mechanism in single module and the sectional elevation of the structure showing the overall constraints in: (a) CLT volumetric structures; (b) CLT platform structures; (c) CLT balloon structures.

Fig. 6. Illustrations of model installation and details of interlocking connections on timber modules.



(a) (b)

Fig. 7. Interlocking connection-reinforced timber modules under (a) lateral and (b) vertical load.

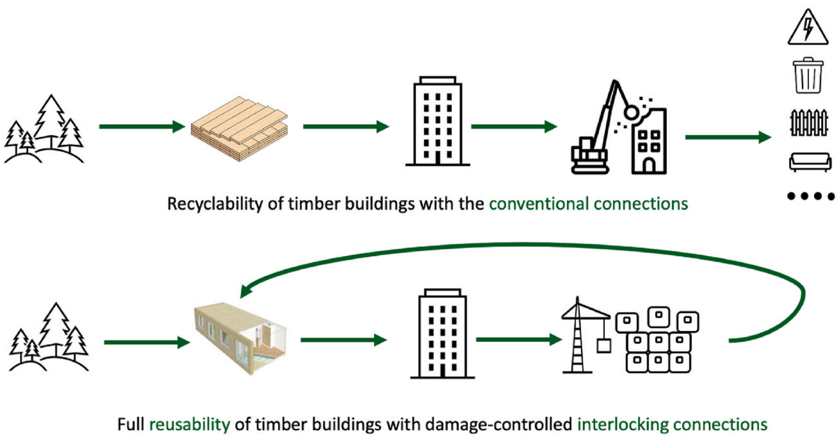


Fig. 8. Comparison of potential building life cycles between CLT structures utilising conventional connections (top) and MOD-IT connections (bottom).

full-scale buildings are still awaiting to be verified.

3.3. Deconstruction and reuse with the interlocking connection

Based on Table 1, the DfR performance of the proposed connection can be summarised as in Table 2.

It can be concluded that, in addition to the potential in improving assembly efficiency, the implementation of novel interlocking connections in building construction also offers significant benefits in terms of deconstruction, material reuse, and circularity. This innovation facilitates a shift away from the linear "take-make-dispose" approach towards a more sustainable circular economy model [15,41] (Fig. 8), enabling careful dismantling and repurposing of materials to extend their usage, reduce waste, and promote sustainable resource utilisation. Ultimately, this approach minimises reliance on new resources and raw material demand, thereby decreasing the environmental footprint associated with material extraction and production processes. This strategy is in line with the principles of circularity within the Architecture, Engineering and Construction (AEC) sector.

However, it is important to recognise that the installation flexibility offered by interlocking connections may lead to inconsistent mechanical properties and tolerances that limit their application in tall buildings [8,32]. In addition, although these connections facilitate material reuse by preserving structural members during deconstruction, these members may still suffer from deteriorated mechanical properties over time due to environmental exposure and gravity [42]. Therefore, the reuse of reclaimed material should also consider subsequent impact of these factors [43], which requires accurate assessment through non-destructive testing methods or advanced health-monitoring technologies.

3.4. Autonomous/robotic construction with interlocking connection

In addition to the enhanced material circularity, incorporating interlocking connection techniques also holds significant potential for advancing autonomous and robotic construction processes. Initially targeting construction in extreme environments, autonomous construction also presents an efficient solution to skilled labour shortages, ensuring higher installation accuracy. Conventional construction methods, characterised by material variability and complex connection processes, necessitate diverse handling and assembly methods and severely limit the feasibility of autonomous construction [44]. In contrast, modular construction with interlocking connections simplifies installation and supports the application of autonomous techniques. The precision of interlocking connections enables robotic systems to assemble and disassemble flat modules with high accuracy and speed, improving productivity and reducing labour costs. Moreover, the modular approach simplifies the hardware design and motion planning of object placement in three-dimensional space, reducing the six degrees of freedom typically required to just four [44].

Presently, research on autonomously installed modular systems is predominantly confined to highly structured laboratory settings. Terada and Murata [44] introduced a dual-handed assembler robot connected by a central arm, designed to automate the assembly process in modular construction with cube-shaped modules and standardised interlocking connections (Fig. 9).

Allwright et al. [45] developed SRoCS, a novel construction platform that combines mobile robots with stigmergic blocks (Fig. 10). These building blocks, each marked with barcodes component labelling and connected via spherical magnets, allow the robots to self-localise in relation to the individual blocks and the structure under construction.

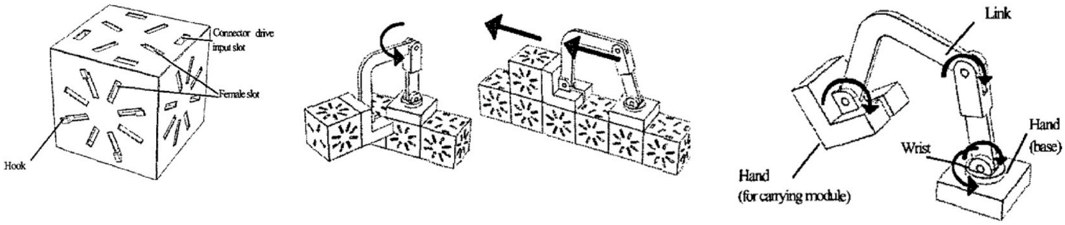
Autonomous timber modular construction, valued for its lightweight nature and the broad possibilities for prefabrication and customisation with standardised components, holds significant promise. Adel et al. and Thoma et al. [47,46] explored the creation of robotically fabricated timber frame structures with 487 timber beams (DFABHOUSE, see Fig. 11). Robots were employed for sizing, drilling, and precisely positioning the beams. Nonetheless, the assembly in this project encountered challenges such as material quality and tolerance variations, robotic mechanical stiffness constraints, and the impact of screw connections, often necessitating human oversight for exact alignment and control.

Another project named CantiBox, is conducted by Tanadini et al. [48] to explore the design and fabrication of a structure composed of three units that are formed by linear timber elements (Fig. 12). Unlike the DFABHOUSE project, CantiBox project achieved fully autonomous construction using remote-controlled robotic clamps and screwdrivers. Customised interlocking timber connections facilitated efficient handling and secure fastening by robots, demonstrating effective automation integration in timber construction.

Rogeau et al. [49] explored how design parameters of through-tenon joints affect robotic assembly through robotic insertion tests (Fig. 13). Their findings indicate that connection design and tolerance significantly impact assembly efficiency and friction forces,

Table 2
DfR performance assessment of MOD-IT connections.

KPIs	Connection performance	Weighing
Connection Type	Building components can be directly separated without the need for working at height or onsite unscrewing/denailing	1.00
Connection Uniformity	The system comprises different connections for shear and tensile reinforcement	0.50
Connection Complexity	The connections can be directly attached to the surface of timber panels without cutting	1.00
Connection Standardisation	Connections are compatible with a wide range of structural element specifications, facilitating easy standardisation and commercialisation	1.00
Connection Prefabrication	Connections can be pre-screwed onto panels in the factories and be ready for direct assembly on-site	1.00
Connection Deformation	In-service deformation is processed in the connection systems while preserving the integrity of structural components	1.00
Connection Accessibility	The connections are easily accessible by removing finishing	0.67
Ease of Transportation	Complete structural components can be detached from buildings, although heavy machinery may be required for transportation	0.10



(a) (b) (c)

Fig. 9. Hardware design of module assembler robot by Terada and Murata [44].

(a) (b)

Fig. 10. Prototypes of (a) the stigmergic building block and (b) the mobile robot [45].

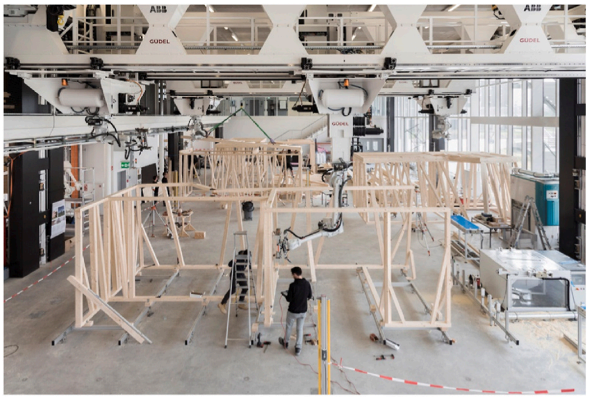


Fig. 11. The assembly of the DFABHOUSE [46].

noting that inadequate tolerance levels cause excessive friction, while excessive tolerance may compromise joint stability.

The exploration of autonomous modular construction showcases the potential for robotic technologies and interlocking techniques to enhance construction accuracy, safety, and efficiency. Thus, it is reasonable to assert that the proposed metal interlocking system for timber modular structures is notably promising in autonomous settings [50]. Furthermore, once completed, these structures embody Kobori et al., 's 1988 concept of "Dynamic Intelligent Buildings" [51], actively adapting to environmental changes, societal demands, and technological advancements, and integrating into the information network to unify lifeline systems within urban communities, reflecting a forward-thinking construction approach where buildings are dynamic participants in urban infrastructure.

4. LCA study

To explore the efficacy of interlocking connections in supporting CE, a preliminary comparative LCA study with an extended cradle-to-cradle (C2C) was conducted. This study compared the global warming potentials (GWPs) associated with the construction, recycling, and reuse of timber modular buildings in three different configurations: a CLT panelised building with conventional metal plate connections (Case 1), a similar structure with MOD-IT connections (Case 2), and a CLT volumetric system also featuring MOD-IT connections (Case 3).

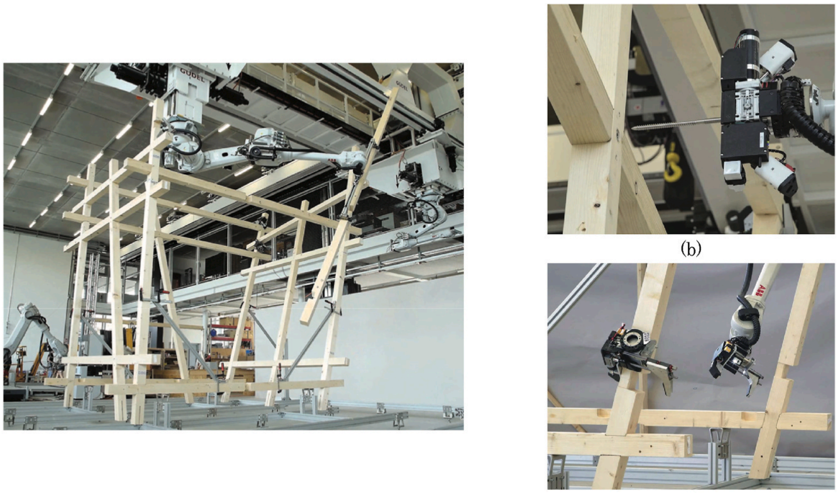


Fig. 12. Construction of CantiBox: (a) timber units during construction with the robotic arm; (b) robotic screwdriver on key components; (c) interlocking connections in the structures assembled by the robotic arm [48].

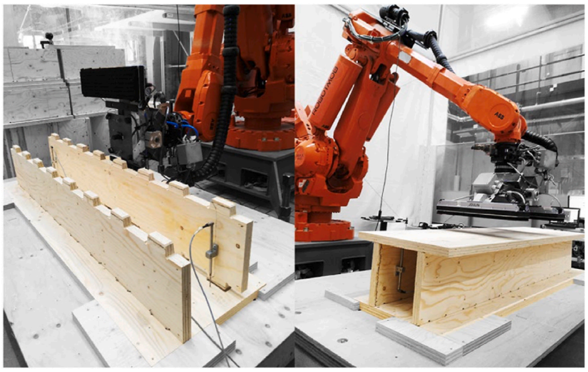


Fig. 13. Robotic assembly of a box girder with through-tenon joints [49].

Due to limited construction data, the LCA relied on available data and assumptions from publications and Environmental Product Declarations (EPDs). Factors such as land use, labour costs, windows, doors, paints, and stairs were excluded due to their minimal emission contribution and negligible differences across systems. The operational phase was also omitted, as it is not central to this research and shows little variation among structural systems [52].

4.1. Case study

The study focuses on a fictional modular CLT construction designed as a six-story residential building, with all three case studies conforming to Eurocode 5 [53]. The building height is restricted to 18 m to comply with the UK fire regulations. The structural system (load-bearing system), the skin (insulation) and the interior (plasterboard) of buildings were considered in this LCA. To facilitate a fair comparison, all models were standardised to have identical load conditions, functionalities, layouts, and building heights (Fig. 14). The reinforced concrete (RC) strip foundations were individually adapted for each building to accommodate the different weights of CLT panelised and volumetric structures. The exterior walls of all buildings are insulated with rockwool and plasterboard, with the insulation thickness across the board fine-tuned to achieve a uniform U-value for the building envelope to ensure functional equivalence. Furthermore, the CLT components, including walls, roofs, slabs, and ceilings, were designed to comply with a minimum fire resistance criterion of 1 h (REI60) based on The Building Regulations [54]. Detailed design information for all case buildings is listed in Fig. 14, Tables 3 and 4.

4.2. System boundaries of case study buildings

In this analysis, the buildings are presumed to have a lifespan of 50 years, with the insulation expected to be replaced every 20 years to maintain energy efficiency and comfort. The CLT and other metal connector are assumed to have overall life span of 100 years that can cover two building lifecycles. To evaluate the sustainability of reusing materials in new construction projects, the study explores two lifecycle scenarios for the buildings, situating one in the heart of London and the other in Leeds. Fig. 16 illustrates the

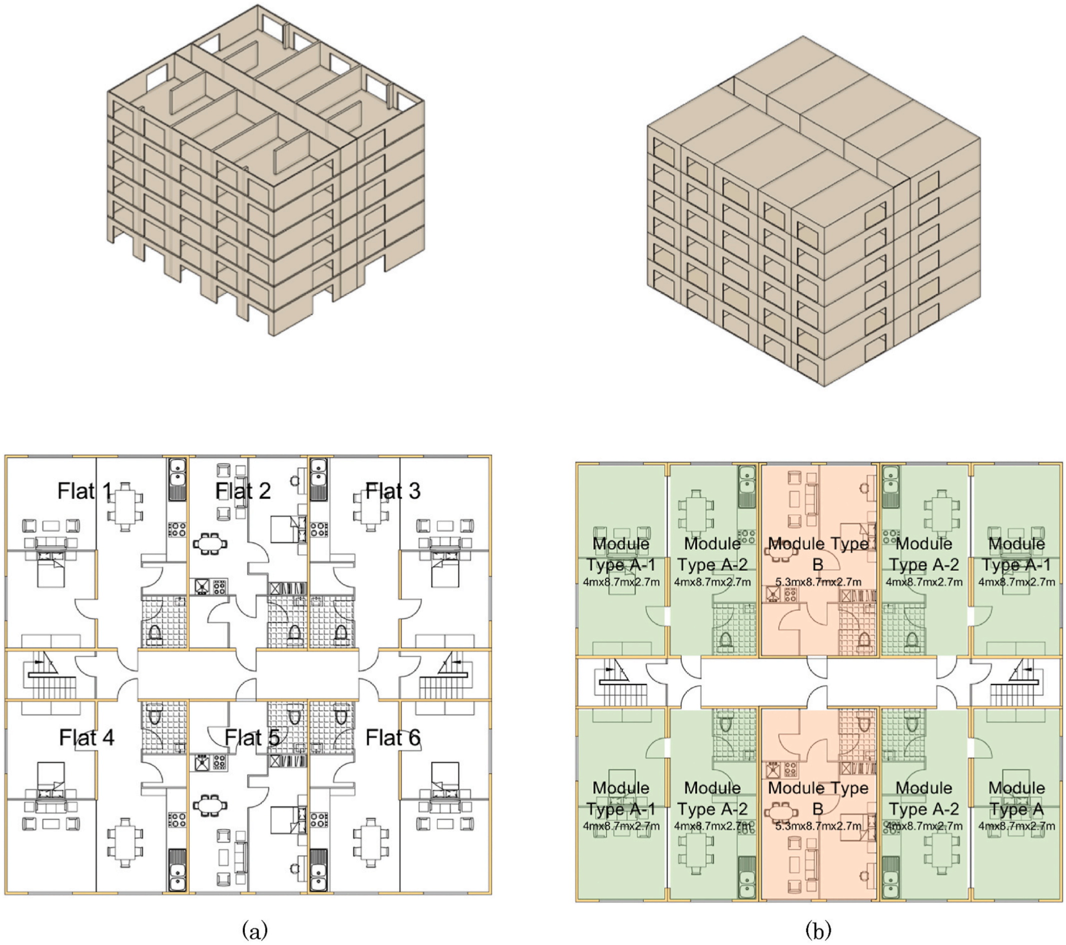


Fig. 14. Floor plans and overall structure of the (a) panelised building and (b) the volumetric buildings.

Table 3
Design details of the CLT panelised building.

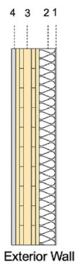
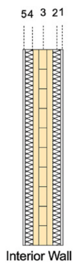
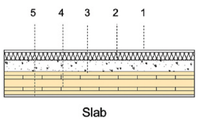
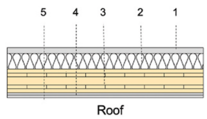
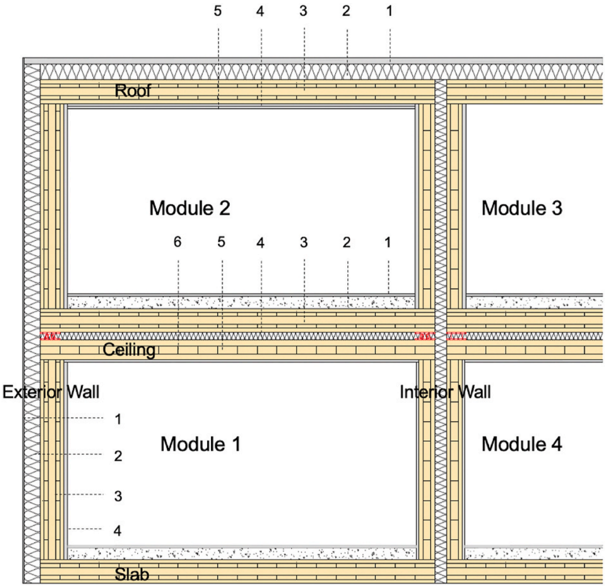
CLT Panelised Building			
	1–7 mm External Plasterboard 2–80 mm Mineral wool 3–120 mm CLT 4–20 mm Plasterboard U value 0.279 W/m^{2}K Fire Rating 1.5Hr		1–12.5 mm Plasterboard 2–40 mm Mineral wool 3–90 mm CLT 4–40 mm Mineral wool 5–12.5 mm Plasterboard U value 0.293 W/m^{2}K Fire Rating 1.5 Hr
	1–12.5 mm Plasterboard 2–45 mm Mineral wool 3–60 mm Soft impact sound insulation 4–160 mm CLT 5–12.5 mm Plasterboard U value 0.230 W/m^{2}K Fire Rating 1.5 Hr		1–30 mm Decking 2–80 mm Mineral wool 3–160 mm CLT 4–12.5 mm Plasterboard 5–12.5 mm Plasterboard U value 0.269 W/m^{2}K Fire Rating 1.5 Hr

Table 4
Design details of the CLT volumetric building.

CLT Volumetric Building



Slab + Ceiling	**Roof**
1–12.5 mm Plasterboard	1–30 mm Decking
2–40 mm Soft impact sound insulation	2–80 mm Mineral wool
3–120 mm CLT	3–120 mm CLT
4–40 mm Mineral wool	4–12.5 mm Plasterboard
5–90 mm CLT	5–12.5 mm Plasterboard
6–12.5 mm Plasterboard	U value 0.269 W/m^{2}K
U value 0.229 W/m^{2}K	Fire Rating 1.5 Hr
Fire Rating 1.5 Hr	
Exterior Wall	**Interior Wall**
1–7 mm External Plasterboard	1–12.5 mm Plasterboard
2–80 mm Mineral wool	2–80 mm CLT
3–120 mm CLT	3–60 mm Mineral wool
4–12.5 mm Plasterboard	4–80 mm CLT
U value 0.282 W/m^{2}K	5–12.5 mm Plasterboard
Fire Rating 1.5Hr	U value 0.300 W/m^{2}K
	Fire Rating 1.5 Hr

comprehensive LCA boundary systems for the case study buildings, which are expanded to include C2C aspects, in alignment with EN 15978 [55].

4.2.1. Production stage (A1-A3)

The production stage of building materials (Module A1-A3) is consistent across all cases, with carbon emission data obtained from product- and company-specific EPDs, alongside supplemental information from generic databases and literature. It is posited that CLT are supplied by Stora Enso in Austria, and metal connections and screws are sourced from Joma AB in Sweden, with all other materials sourced locally to minimise transportation emissions. Given that MOD-IT connections are still in the developmental phase and has not been widely commercialised, the study assumes that these components would also be supplied by Joma AB.

4.2.2. Transportation and construction stage (A4&A5)

For the transportation phase (Module A4), in Cases 1 and 2, construction materials are transported directly to the building site for both building lifespans. In Case 3, however, CLT and insulation panels are first shipped to a local volumetric manufacturer near London for pre-assembly into modules before being transported to the construction site (Fig. 15). The transportation modes, distances, and associated emission factors used in calculation are based on a recent publication regarding mass timber transportation in UK construction [56]. In Module A5, emissions were calculated using data from the EPDs, focusing primarily on construction waste processing, as element assembly was excluded due to the variability in onsite equipment and labour requirements.

4.2.3. EoL and post-use stages (C1-C4)

Since most current CLT buildings are pioneers in their field and have not yet reached the end of their service life [2,57], there is a lack of actual data for the EoL stage in LCA studies, making informed assumptions becomes crucial for a comprehensive LCA

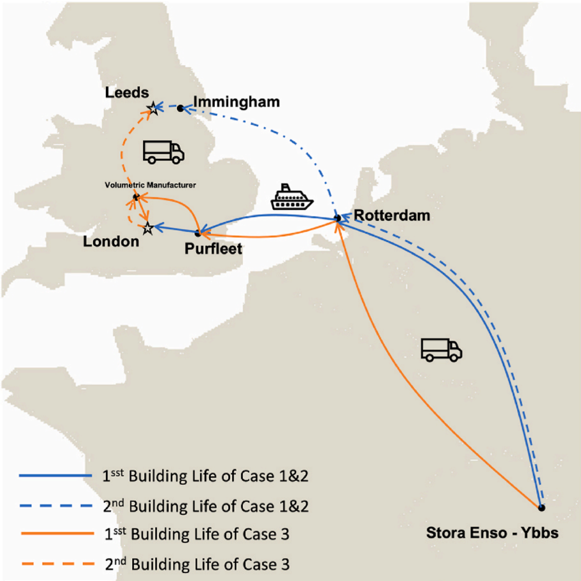


Fig. 15. CLT transportation plans in LCA.

methodology. For materials other than CLT, the EoL scenario allocation adheres to the guidance provided by EPDs, previous literature [2], or published statistics [17]. A key element at the EoL stage involves the processing of CLT material post-demolition or deconstruction (Module C1-C4), with potential scenarios including partial or complete reuse, incineration with or without energy recovery, and landfill disposal. The EDP from Stora Enso offers data on the environmental impacts of these various EoL scenarios.

In this analysis, a mix of different EoL scenarios is assumed for the CLT used in each case study building, considering their specific connection systems and structural configurations (Fig. 16). For example, the panelised building with conventional connections (Case 1) may result in materials being recycled as wood chips due to demolition-induced damage, whereas panels with MOD-IT connections (Case 2) could be fully disassembled and repurposed as timber lumber for new CLT material production. Regarding the volumetric building, the modular CLT units are anticipated to be entirely reusable, attributable to the damage mitigation features inherent in MOD-IT connections.

In the subsequent lifecycle of buildings in Case 1 and Case 2, all newly required materials are transported directly to the second construction site for assembly on-site. For Case 3, the disassembled modules are first sent back to the manufacturer with the MOD-IT connections for maintenance and adding new insulation before being moved to the next site, thus eliminating the need for waste processing and disposal of structural and connection material. Upon completing the second building lifecycle, the CLT modules, having reached their lifespan limit of 100 years, are anticipated to be recycled. The carbon savings from reclaimed materials (Module D of Case 3) are fully attributed to the subsequent building system, while the environmental impact was evaluated separately for each building system. This approach aims to quantify the environmental impacts of each building layer and evaluate the environmental impact during the reuse phase, highlighting the benefits of repurposing materials in new builds.

4.3. LCA results and discussion

Fig. 17 illustrates the carbon emissions for three case study buildings over their initial and subsequent life cycles. For all buildings, CLT usage is one of the largest contributions in overall carbon emission. Due to similar structural designs, Cases 1 and 2 maintain a consistent carbon footprint related to CLT utilisation. In contrast, the volumetric building (Case 3) - characterised by its double-ceiling and double-wall configuration - exhibits a higher material demand, consequently elevating the carbon emissions associated with CLT and foundational materials (concrete and steel reinforcement).

In the second lifecycle, both Case 1 and Case 2 buildings show a rise in CLT carbon emissions, primarily due to increased transportation distances to new sites. Conversely, while the Case 3 building also involves carbon emissions related to CLT, these are primarily associated with the transportation of disassembled modules and their reassembly at the new location, resulting in emissions 65 % lower than Cases 1 and 2. Given that this study excludes the operational phase (Module B) from consideration, the predominant portion of the carbon emissions in all three buildings are potentially offset.

Another critical contributor to carbon emissions in CLT modular constructions with MOD-IT connections is the quantity of connection material. Traditional connection methods result in the lowest carbon emissions due to their lightweight and discrete reinforcing method. In contrast, the panelised building in Case 2 (Fig. 18), makes extensive use of interlocking connections and screws due to its continuous reinforcement strategy, resulting in the highest carbon emissions among the connection materials. This highlights the incompatibility of this continuous interlocking connection with CLT panelised structures, despite their theoretical feasibility as previously discussed.

On the other hand, the CLT volumetric building requires interlocking connections only along the shorter edges of CLT modules

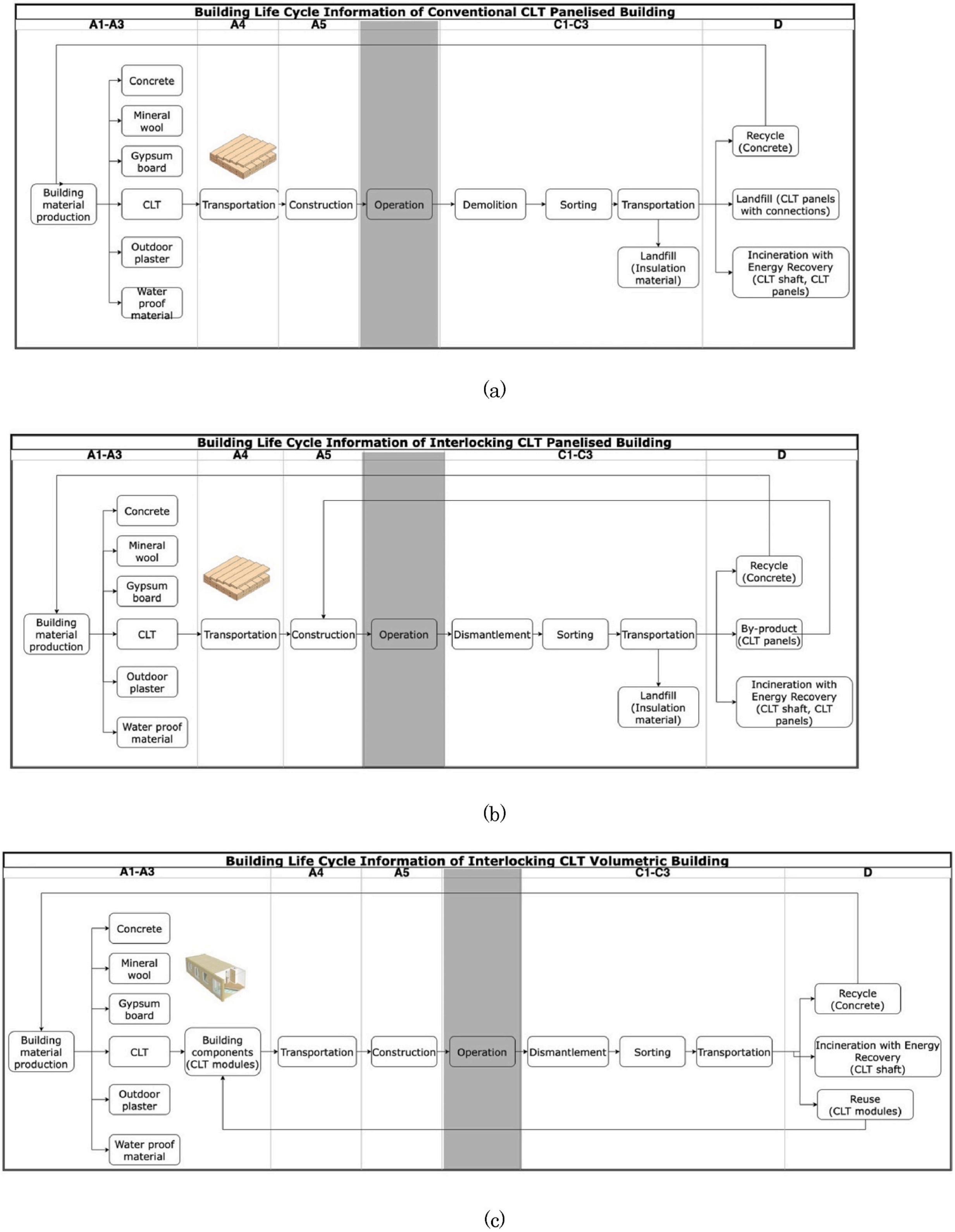


Fig. 16. LCA system boundaries of (a) the conventional CLT panelised buildings (Case 1); (b) the interlocking CLT panelised buildings (Case 2); (c) the interlocking CLT volumetric buildings (Case 3).

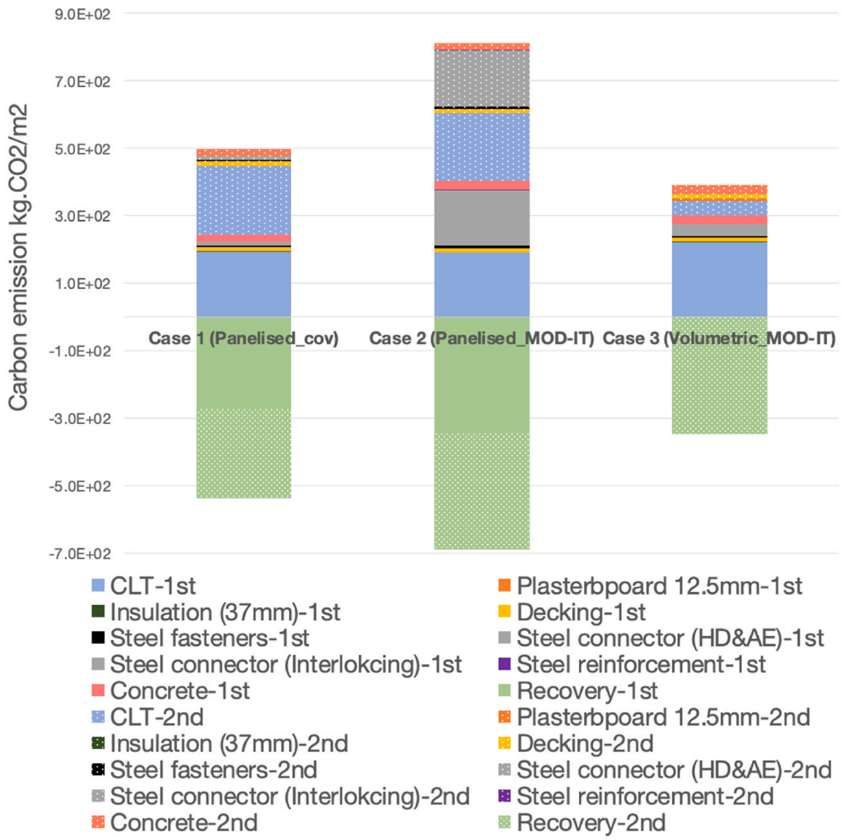


Fig. 17. Contribution of different building components to the carbon emission.

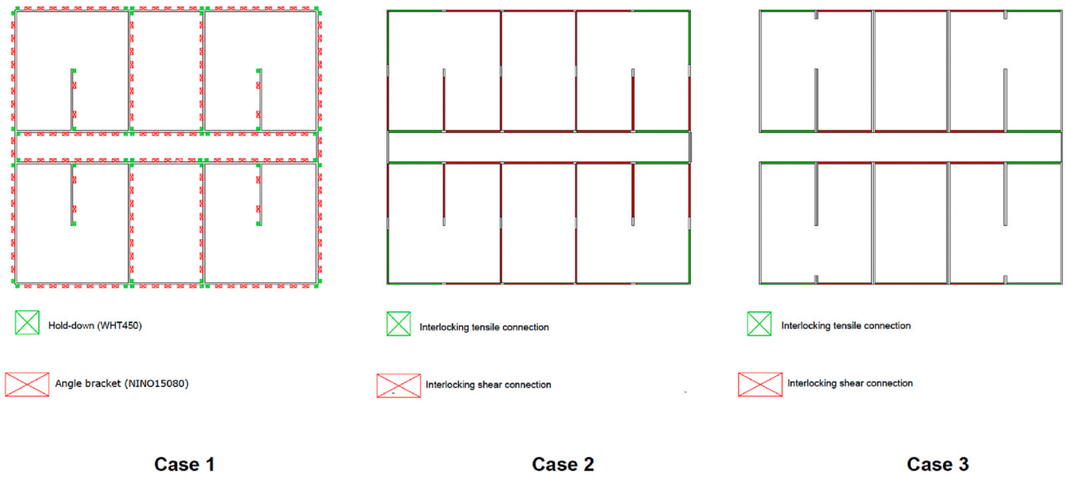


Fig. 18. Interlocking connection locations in different buildings.

(Fig. 18), thereby reducing the material needed for connections compared to the panelised structure in Case 2, although still exceeding that of traditional plate connections. Remarkably, Case 3 uses 86 % fewer fasteners in connectors than Case 1 and 67 % fewer than Case 2, achieved by using larger-diameter screws in much smaller quantities, thanks to the 'damage-controlled' capacity of the interlocking connections [40]. This feature also facilitates the reuse of CLT materials in Cases 2 and 3, resulting in a 45 % higher energy recovery in Module D compared to Case 1.

Fig. 19 illustrates the carbon emissions at various stages of CLT modular construction, highlighting that the manufacturing phase (A1-A3) is the predominant source of carbon footprint for all case study buildings, accounting for 48.1 %, 66.5 % and 56.2 % of total

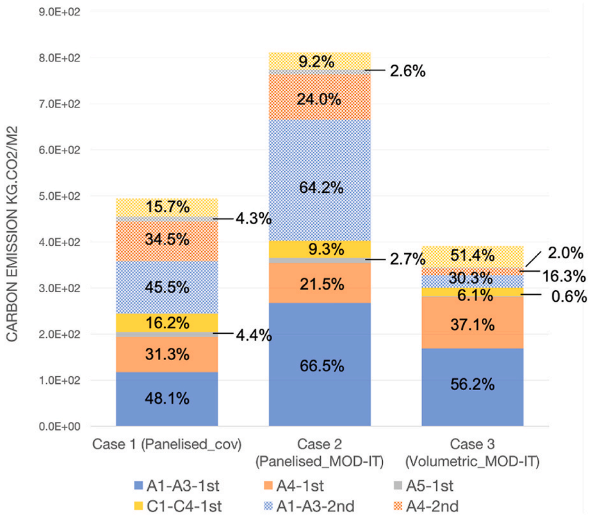


Fig. 19. Relative contributions of the building's life cycle stages to the environmental impacts (Note: The above percentages refer to the proportion of each stage within their respective building life cycles.).

emission for Case 1, Case 2 and Case 3 building, corresponding to the previous LCA on the low-to mid-rise CLT panelised [58,59] and volumetric buildings [59,60], respectively. At this stage, the case 1 building has the lowest carbon emission (56.16 % less than case 2 and 30.5 % less than case 3). This reduction is attributed to the minimised use of materials in steel plate connections and the timber in the panelised structure, which also results in the lowest total amount of lifecycle emissions for transportation (A4). In contrast, the Case 2 building records the highest carbon emissions during the production stage due to the extensive use of continuous interlocking connections. It should also be noted that carbon emissions from transportation are more significant in CLT construction (accounting for 20–40 %) compared to other construction methods, primarily due to the relatively lower embodied carbon of CLT compared to conventional materials, as supported by other publications [56].

In Case 3, full reusability of the building was assumed, eliminating the need to process construction waste. This led to significant carbon reductions in stages C1 to C4 of the first building life and stages A1 to A3 of the second life. Although Case 3 had 23 % higher carbon emissions in its initial life compared to Case 1 due to its volumetric structure and interlocking connections, substantial carbon savings (21 % reduction) were achieved in the second life by reusing the entire timber module. The primary contributors to this reduction were the avoidance of manufacturing and importing raw materials. This suggests that in construction locations requiring CLT imports, reusing materials domestically can significantly lower emissions for new builds.

4.4. LCA conclusions

While this initial LCA study may not predict fully the carbon emissions of CLT buildings with traditional and interlocking connections, it offers an impartial comparison, demonstrating that interlocking connections can reduce emissions during construction and deconstruction by facilitating material reuse. In CLT volumetric construction, which typically has higher manufacturing emissions, reusing CLT modules with their interlocking connections can significantly lower carbon emissions in new builds and enable greater energy recovery through disassembly instead of demolition. Moreover, studies [60,61] suggest that volumetric construction can reduce material wastage by up to 2.5 times compared to traditional methods. Therefore, when considering the efficiency of volumetric construction and interlocking assembly process (reductions in onsite labour and machinery operation), the potential carbon savings could be even greater.

However, the material demands of continuous interlocking connections, despite their structural and circularity advantages, may lead to higher costs and environmental impacts. This suggests the necessity for further refinement of the geometric design of these connections for improved practicality and environmental sustainability in CLT structures, particularly for their application in CLT panelised structures.

However, this LCA is notably limited by the lack of field data on CLT volumetric structures and interlocking connections. For a more accurate environmental impact assessment of CLT construction with MOD-IT or other kinds of interlocking connections, an even more comprehensive LCA is required. This should include detailed data collection during the pre-assembly, transportation, lifting, assembly, disassembly, and rebuilding processes to precisely evaluate the impact and potential for structural reuse.

5. Discussions

Aligned with the construction industry's shift toward a circular economy, this paper explores how interlocking connection design impacts building circularity. Based on previous research, it proposes a revised DfR guideline to create reusable connections that simplify assembly and disassembly, supporting CE principles in construction. A newly developed metal interlocking connection system for timber modular construction was evaluated against the DfR guideline, demonstrating the strong potential of interlocking connections to more sustainable and resource-efficient building practices. A detailed LCA with a C2C framework was also employed to compare the environmental impacts of a CLT volumetric system utilising the interlocking connections against CLT panelised systems incorporating both interlocking and conventional screwed connections.

However, the integration of interlocking connection systems in construction is still hindered by economic and reliability challenges. These challenges include non-standardised connection designs with significant geometry complexity, construction practices, cost, and reliability. To facilitate the practical application of this kind of connecting technique, future research will be required for the below areas [40].

- The ageing effects (e.g., reverse-cyclic and alternating loading) on long-term performance and reversibility of connections should be thoroughly studied.
- The deconstruction process with interlocking connections should also be experimentally evaluated, focusing on the potential geometrical deviations that occur when structural members are disassembled and reassembled.
- The interaction of demountable connections with surrounding components should be investigated, to ensure that the entire system can work without compromising performance.

6. Conclusion

The study highlighted the considerable advantages of using interlocking connections in promoting material reuse and recycling, then summarised the DfR strategies that can be implemented in connection design, which were then illustrated via a recently proposed conceptual connection system (MOD-IT). In addition to the environmental benefits, the interlocking connection system for timber modular structures stands as a promising innovation in the domain of autonomous construction, due to its simplified assembly nature and the lightweight nature of timber material. Future research will be crucial in addressing these obstacles, enabling the incorporation of these techniques into existing construction methods and realising the full potential of interlocking connections for sustainable construction.

CRediT authorship contribution statement

Zhengyao Li: Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization. **Konstantinos Daniel Tsavdaridis:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Assel Katenbayeva:** Writing – review & editing, Validation, Supervision, Methodology, Investigation.

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.

Data availability

No data was used for the research described in the article.

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